JCMM

Journal of Computers, Mechanical and Management

e-ISSN: 3009-075X

Volume 2, Issue 3

2023

AAN PUBLISHING

eISSN 3009-075X

JCMM Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in e-ISSN: 3009-075X AAN PUBLISHING

Editorial Comments: JCMM Volume 2 Issue 3

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The release of Volume 2, Issue 3 of the Journal of Computers, Mechanical, and Management arrives at an important juncture. Not only does this issue present rigorous scholarly investigations across varied disciplines, it also heralds an organizational transition that opens a new chapter in the journal's history. Transitioning from GADL Publishing, India to AAN Publishing, Malaysia aims to extend the journal's international footprint and elevate the quality of service to the community of authors and readers. The foundational role of GADL Publishing is recognized and appreciated. Additionally, the recent acquisition of an e-ISSN augments the journal's academic standing and promotes broader digital access.

Deepak V Lokare [1] focuses on high-speed machining (HSM) of Aluminum 7075, a subject of significant interest in manufacturing sectors such as aerospace, automotive, and consumer electronics. Through meticulous use of Response Surface Methodology (RSM), the paper identifies the key parameters affecting surface roughness during machining, offering practical implications for industries seeking optimal performance and quality. Nikhil Ranjan's [2] innovative study addresses issues that have long plagued traditional voting processes, such as voter fraud and security lapses. By integrating biometric identifiers like facial recognition and fingerprints into Electronic Voting Machines (EVM), the paper proposes a paradigm shift aimed at creating a more secure and efficient voting ecosystem. This research not only addresses technical aspects but also offers a discussion on the societal implications such as employment impacts and data privacy.

C. Raghavendra Kamath [3] undertakes a comprehensive comparative analysis of packing algorithms used in container packing. Given the increasing focus on logistics and supply chain efficiency, the paper's findings provide invaluable data for optimizing space, thereby having implications for reducing transportation costs and environmental impact. The co-authored paper by Ved Prakash and Shubham Pratap Singh [4] examines the critical dimensions of service quality and customer satisfaction within rural public sector banks. Utilizing the SERVQUAL model, the paper uncovers specific factors that influence customer satisfaction, thus offering actionable insights for policy formulation in the rural banking sector.

A multi-author collaboration, led by Sarvesh Kumar [5], explores the transformative impact of Artificial Intelligence (AI) on cyber security. As cyber threats become increasingly sophisticated, the paper elucidates how AI technologies can outperform human-mediated processes in tasks such as threat detection and vulnerability management. While highlighting the strengths of AI, the study also calls attention to the ethical concerns and governance structures needed for responsible technology deployment. Teresa Castillo Pérez [6] provides an in-depth review on the environmental footprint of lithium-ion batteries used in electric vehicles. This review is timely given the global urgency to transition towards sustainable mobility solutions. By offering a balanced discussion on both the benefits and challenges of lithium-ion batteries, the paper enriches the discourse on sustainable transportation.

Collectively, these contributions in this issue advance scholarly discourse in a range of domains from mechanical engineering to public sector management and cyber security. As the journal steps into a promising new phase under AAN Publishing, continued scholarly engagement and readership is fervently encouraged.

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Published: 31 August 2023

DOI: 10.57159/gadl.jcmm.2.3.23098.

References

[1] D. V. Lokare, “Experimental Analysis of Machining Parameters In Turning of Aluminum 7075,” *Journal of Computers, Mechanical and Management*, vol. 2, pp. 1–8, aug 2023.

[2] N. Ranjan, “Enhancing Voting Security and Efficiency,” *Journal of Computers, Mechanical and Management*, vol. 2, pp. 9–15, aug 2023.

[3] R. Kamath, “Optimizing Space Utilization In Container Packing,” *Journal of Computers, Mechanical and Management*, vol. 2, pp. 16–23, aug 2023.

[4] V. Prakash and S. P. Singh, “Service Quality and Customer Satisfaction in Public Sector,” *Journal of Computers, Mechanical and Management*, vol. 2, pp. 24–30, aug 2023.

[5] S. Kumar, U. Gupta, A. K. Singh, and A. K. Singh, “Artificial Intelligence,” *Journal of Computers, Mechanical and Management*, vol. 2, pp. 31–42, aug 2023.

[6] T. C. Perez, “A Mini-Review of the Environmental Footprint of Lithium-Ion Batteries for Electric Vehicles,” *Journal of Computers, Mechanical and Management*, vol. 2, pp. 43–52, aug 2023.

Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in
e-ISSN: 3009-075X

Volume 2 Issue 3

Article Number: 23061

Experimental Analysis of Machining Parameters In Turning of Aluminum 7075

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Abstract

High-Speed Machining (HSM) of aluminum alloys represents a critical area in manufacturing industries, including automotive, aerospace and consumer electronics. This research presents an in-depth investigation into the effects of key process parameters on the HSM of Aluminum 7075, a high-strength alloy with superior mechanical properties. Utilizing the central composite design of Response Surface Methodology (RSM), the study scrutinizes the impact of process parameters, including cutting speed, feed, depth of cut and tool nose radius on surface roughness. The findings reveal feed and nose radius as primary factors influencing surface roughness while cutting speed and depth of cut play secondary roles. This comprehensive analysis contributes to the knowledge base for efficient machining practices and lays the groundwork for future optimization strategies. It also underscores the necessity for further research into understanding the intricate dynamics of machining parameters to enhance operational efficiency and product quality in the machining of Aluminum 7075 and similar alloys.

Keywords: High-Speed Machining; Aluminum 7075; Process Parameters; Response Surface Methodology; Optimization

1 Introduction

Machining serves as a cornerstone process in the manufacturing industry, enabling the transformation of raw materials into tailored products [1, 2]. Turning, a subset of machining, uses a cutting tool to remove material from a rotating workpiece, creating cylindrical shapes. This process finds application in numerous industries, such as automotive, aerospace, and electronics, due to its versatility and efficiency [3, 4]. Aluminum and its alloys, owing to its lightweight properties, high thermal conductivity, non-toxicity, and recyclability, are indispensable materials across the discussed industries [5]. The high-speed machining (HSM) of aluminum alloys holds immense significance in manufacturing, enhancing productivity and surface finish quality [6–9]. This methodology has displayed notable success in the aeronautics industry, with potential for further optimization [10]. Nevertheless, the HSM of aluminum comes with intrinsic complexities [11, 12]. There is a multitude of process parameters to consider, leading to a lack of consensus regarding the optimal cutting speed for aluminum machining, as initially proposed by Taylor [13]. Critical parameters, such as cutting speed, depth of cut, and feed, have profound implications on surface roughness, which in turn significantly affects the fatigue life of a machined part [14–19]. Other contributing factors include the workpiece material, tooling, and cutting fluid utilization, which markedly influences the cutting forces and chip formation and disposal [20–24]. Within the aluminum family, Aluminum 7075 stands out due to its high strength and superior mechanical properties. Its impressive strength-to-weight ratio, corrosion resistance, and machinability make it the material of choice for high-stress components like aircraft fittings, gears and shafts [25, 26]. However, attaining the desired outcomes, such as optimal surface roughness and material removal rate during the machining of Al 7075, demands rigorous control and optimization of process parameters.

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Received: 14 June 2023; **Revised:** 30 June 2023;**Accepted:** 02 July 2023; **Published:** 31 August 2023

DOI: 10.57159/gadl.jcmm.2.3.23061.

Thus, even in recent times, researchers have been working on the optimization of machining, particulary the turning of Al 7075. For example, Akhtar et al.[27] tried to optimize the turning operation for Al 7075 while focussing on better quality end product. Veluchamy et al. [28] tried to optimize the turning process to obtain better surface roughness. Lakshmanan et al. [29] tried to optimize the turning process for Al 7075. While previous work on Al7075 turning has primarily focused on optimizing the process of turning Al 7075 at comparatively low speed range, this study seeks to contribute to the existing literature by providing an in-depth exploration into the effects of key process parameters on the HSM of Aluminum 7075 alloy. Utilizing the central composite design method of Response Surface Methodology (RSM), an exhaustive investigation into the effects of cutting parameters, including cutting speed, feed, depth of cut and tool nose radius on surface roughness is conducted. Through this rigorous investigation, the study aims to provide significant insights for efficient machining practices and advance the body of knowledge in the realm of aluminum high-speed machining.

2 Materials and Methods

2.1 Material

The chosen workpiece material for this study is Al 7075 high-strength alloy. This alloy is primarily used in demanding applications, especially in aircraft structures, due to its excellent ductility, strength, fracture toughness, low density, and resistance to corrosion and fatigue [30–32]. Al 7075 is commercially extracted from Bauxite using the Hall (Heroult) process, then further purified to yield 99.9% pure aluminum [33]. The chemical composition and specific material properties of the Al 7075 alloy used in the present study are outlined in Table 1 and Table 2, respectively.

Table 1: Chemical composition of Al 7075 alloy.

Elements	Zn	Mg	Cu	Cr	Mn	Si	Fe	Ti	Al
Wt. %	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.28	$<$0.3	$<$0.4	$<$0.5	$<$0.2	87.1-91.4

Table 2: Material properties of Al 7075 alloy

Material properties	**Al 7075**
Physical density	2.8 g/cm^3
Ultimate tensile strength	220 MPa
Yield strength	95 MPa
Brinell hardness number	60
Elongation at break	17%
Modulus of elasticity	70-80 GPa

2.2 Machining setup

The high-speed turning experiments were conducted on a FANUC series Oi-TC model CNC lathe featuring a three-jaw independent chuck, a computer numerically controlled tool slide, and an automatic lubrication motor. The fixture used was a hydraulic-operated, three-jaw self-centering chuck. The lathe was equipped with a PCLNL 2525 M12 tool holder, which housed a CNMG 120408 cutting insert. This insert was characterized by a diamond 80 shape, zero-degree clearance angle, 0.002 mm tolerance, and a clamp-on with a chip breaker. The jigging fixture was designed with specific resting, location and clamping points on the workpiece's diameter, with the resting point at the end face. Figure 1 depicts the discussed setup.

2.3 Experimentation and data analysis

The present subsection outlines the experimental setup and methodology used to gather and analyze data. It's important to note that these are standard practices in conducting an experimental study, with each step in the process having a purpose in ensuring the accuracy and relevancy of the results. A total of 27 experiments were performed based on a face-centered central composite design using response surface methodology, which refers to a specific experimental design model used in optimization processes, often when investigating the response of a system to various parameters. The number of experiments (27 in this case) is determined by the factorial of the levels of the parameters and the total number of parameters. The response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for developing, improving, and optimizing processes, where the main idea is to use a sequence of designed experiments to obtain an optimal response. Four crucial machining parameters - cutting speed, feed, depth of cut, and tool nose radius - were varied at three levels each, with operating levels for these parameters presented in Table 3.

Figure 1: Machining setup used for the HSM of Al 7075 alloy

Table 3: Input machining parameters and their operating levels.

Sl. No.	Cutting parameters	Units	Notation	Levels		
				Low	Medium	High
1	Cutting speed, V	rpm	A	94	188	282
2	Feed rate, f	mm/rev	B	0.2	0.3	0.4
3	Depth of cut, d	mm	C	0.8	1.4	2.0
4	Tool nose radius, r	mm	D	0.4	0.8	1.2

Regression analysis was used for the development of a model for machining quality characteristics. Regression analysis is a statistical process for estimating the relationships among variables. It includes techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. Here, it is used to create a model that can predict machining quality based on the four parameters. The collected data were subjected to Analysis of variance (ANOVA) to statistically estimate the influence of full quadratic factor effects. Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences among group means and their associated procedures. In the present case, it is used to understand how much of the variance in the response, or dependent variable, can be explained by the four machining parameters. Surface roughness is a key measure of the quality of a machined surface and is typically measured using a specific instrument. In this case, a SurfCom Flex 50 surface roughness measuring instrument was used to measure surface roughness at nine different locations on the sample. The average value of these measurements was then used for model development and evaluation. By taking measurements at multiple locations, the model is made more robust and representative of the entire surface, reducing the influence of outlier measurements.

3 Results and Discussion

The experimental design was formulated using the response surface methodology (RSM) in a central composite design (CCD). Table 4 presents the values of each parameter at their respective levels, along with the corresponding surface roughness measurements. An initial inspection of the raw experimental data reveals several noteworthy trends. It is evident that an increase in cutting speed and feed while keeping a low tool nose radius oftenly resulted in a higher surface roughness (Ra), possibly due to increased vibrations and chip load. Conversely, slower cutting speeds and lower feed rates, especially when coupled with larger tool nose radius, seem to improve surface roughness, potentially providing better control over the cutting process. The depth of cut also seem to play a significant role as with a higher depth of cut in combination with a smaller tool nose radius tend to increase surface roughness. This might be probably due to increased interaction of the tool with the workpiece material. It's essential to emphasize that these are preliminary observations. Thus, to obtain a better understanding of these relationships and their statistical significance, rigorous statistical analysis, such as a regression analysis and ANOVA was conducted. The ANOVA was used to test the significance of each of the model terms (factors and interactions) in explaining the variability in surface roughness. The factors included linear, square and 2-way interaction components of each variable.The resulting ANOVA for the investigated factors and the obtained response is reported in Table 5. The Adj SS (Adjusted sum of squares) represents the variability due to each term, while the Adj MS (Adjusted mean square) is the average variability due to each term. The F-value is used to test if the variability contributed by each term is significant. The results show that the feed (f) and nose radius (r) have the highest individual F-values (806.82 and 630.74 respectively), indicating that they have a strong influence on surface roughness. However, cutting speed (V) and depth of cut (d) have low F-values, suggesting that they have a lesser impact on surface roughness. Furthermore, the 2-way interaction between feed rate and nose radius (fr) also has a high F-value (176.71), indicating that the interaction of these two factors significantly influences the surface roughness. This could be due to the fact that the feed rate and tool nose radius are two of the most influential cutting parameters on surface roughness quality.

Table 4: Machining parameters and surface roughness.

Cutting Speed V(rpm)	Feed, f (mm/rev)	Depth of cut, d (mm)	Nose radius, r (mm)	Surface roughness, Ra (microns)
2000	0.3	1.4	0.4	6.86
1000	0.4	2	0.4	11.486
2000	0.2	1.4	0.8	1.166
3000	0.4	2	1.2	4.079
1000	0.2	0.8	1.2	1.085
1000	0.2	2	1.2	0.939
3000	0.4	2	0.4	11.156
3000	0.2	2	1.2	1.084
1000	0.4	0.8	0.4	11.271
1000	0.4	0.8	1.2	4.032
2000	0.3	0.8	0.8	2.851
3000	0.2	2	0.4	3.574
2000	0.4	1.4	0.8	4.848
2000	0.3	1.4	1.2	2.594
1000	0.2	2	0.4	2.698
1000	0.3	1.4	0.8	2.88
2000	0.3	1.4	0.8	2.719
3000	0.4	0.8	1.2	3.788
1000	0.2	0.8	0.4	3.1
2000	0.3	1.4	0.8	2.95
3000	0.2	0.8	1.2	1.098
2000	0.3	2	0.8	2.936
3000	0.3	1.4	0.8	2.742
1000	0.4	2	1.2	3.781
2000	0.3	1.4	0.8	2.889
3000	0.4	0.8	0.4	11.217
3000	0.2	0.8	0.4	3.256

Experimental results have shown that for a fixed high cutting speed, tool nose radius, and a sharp cutting tool, surface roughness increases with increasing feed rate [34]. The interaction between these two factors can affect the contact area between the tool and workpiece material, which in turn can influence the surface quality.

Table 5: ANOVA results for surface roughness

Source	DF	Adj SS	Adj MS	F-Value
Model	14	275.675	19.691	125.91
Linear	4	224.857	56.214	359.44
V	1	0.029	0.029	0.19
f	1	126.182	126.182	806.82
d	1	0.000	0.000	0.00
r	1	98.645	98.645	630.74
Square	4	22.934	5.733	36.66
V^2	1	0.006	0.006	0.04
f^2	1	0.055	0.055	0.35
d^2	1	0.003	0.003	0.02
r^2	1	8.955	8.955	57.26
2-Way Interaction	6	27.885	4.647	29.72
Vf	1	0.144	0.144	0.92
Vd	1	0.078	0.078	0.50
Vr	1	0.012	0.012	0.08
fd	1	0.012	0.012	0.08
fr	1	27.636	27.636	176.71
dr	1	0.002	0.002	0.01
Error	12	1.877	0.156	
Lack-of-Fit	10	1.848	0.185	12.90
Pure Error	2	0.029	0.014	
Total	26	277.55		

The corresponding regression equation in uncoded units was developed and represented by Eq [1]. The equation provided represents a multiple regression model for surface roughness (Ra) as a function of the machining parameters and their interactions. The coefficients in front of the machining parameters (V, f, d, r) and their interaction/square terms represent their effects on surface roughness. The positive coefficients suggest that an increase in the corresponding parameter would increase surface roughness, while the negative coefficients suggest that an increase in the corresponding parameter would decrease surface roughness. For example, the negative coefficient -45.3 in front of the feed rate (f) suggests that an increase in feed rate would significantly decrease surface roughness. However, interpretation of the coefficients should be done with caution, particularly for those parameters involved in the interaction terms. For example, the interaction term between feed rate and nose radius (fr) has a coefficient -32.86, meaning that the combined effect of feed rate and nose radius decreases surface roughness more than what would be predicted by their individual effects.

$$
\begin{aligned}
Ra = & 0.17 + 0.00042V - 45.3f - 0.58d - 14.45r0.000000V^2 + 14.6f^2 + 0.091d^2 + 11.66r^2 \\
& - 0.000950Vf + 0.000116Vd - 0.000068Vr + 0.46fd - 32.86fr - 0.049dr
\end{aligned} \tag{1}
$$

The residual, the difference between the experimental and theoretical values, was assessed to gauge the performance of the model. As depicted in Figure 2, the discrepancy between the observed and predicted values did not exceed 0.8, falling within an acceptable margin of error. This suggests that the model is reasonably accurate in forecasting the surface roughness based on the machining parameters and their interactions. This minor discrepancy can be attributed to unavoidable variations in the machining environment, such as fluctuations in machine stability, tool wear, temperature changes, or measurement uncertainties. Despite these inevitable variations, the model's high accuracy underscores its robustness and practical applicability in predicting the surface quality in machining processes. It is crucial to remember that while this model is powerful and has demonstrated accuracy within the scope of this study, every prediction model has its limitations. This model is expected to work best within the range of parameters tested in this study. Using it beyond these parameters may require additional validation to ensure its accuracy.

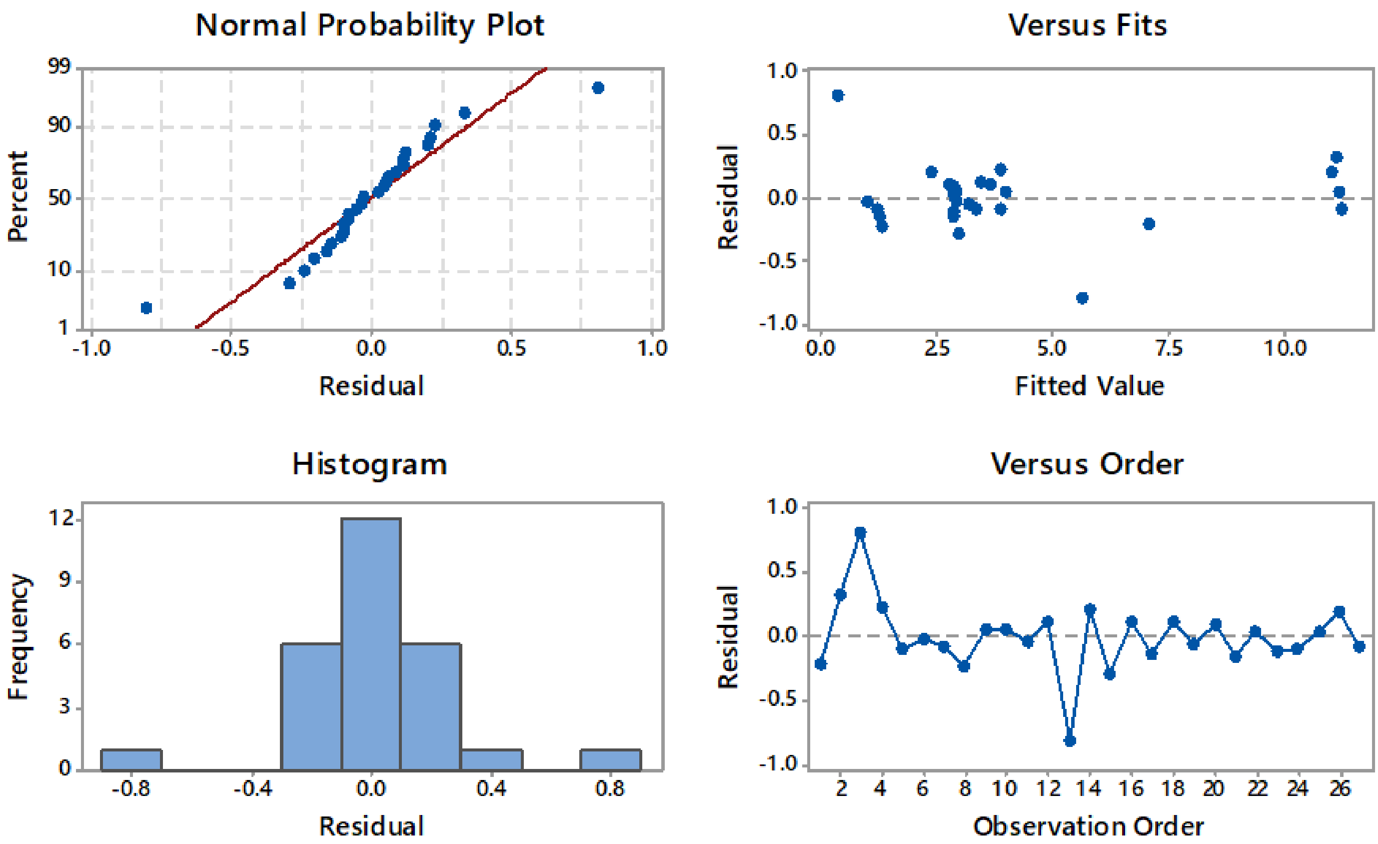

Figure 2: Residual plots for surface roughness

The main effect plots are graphical representations that show the relationship between the dependent variable (in this case, surface roughness) and each of the independent variables (cutting parameters). These plots allow for an intuitive understanding of the impact of each parameter on surface roughness. In Figure 3, the main effects of each factor on surface roughness are displayed. It is seen that feed rate and tool nose radius have a pronounced impact on surface roughness compared to the cutting speed and depth of cut. This reinforces the results from the ANOVA and regression analyses, confirming that these parameters are the primary influencers on surface roughness. While these findings provide valuable insights into the behavior of the system, the study is not without its limitations. Inherent discrepancies between experimental and theoretical values could be attributed to uncontrollable factors, often referred to as "noise," in the machining environment.

Noise can come from a range of sources, such as machine vibration, thermal fluctuations, and even potential human errors in the measurement process. As for future studies, broadening the scope of the analysis to include other potentially influential variables would be beneficial. This might involve looking at different tool materials, workpiece materials, coolant types, or environmental conditions, to name a few. By examining these additional variables, we can gain a more holistic understanding of the machining process, allowing us to better predict and control surface roughness in CNC lathe machining. In essence, understanding how different factors contribute to the final output is key to optimizing the machining process, and further research in this area can lead to significant improvements in surface quality and overall machining efficiency.

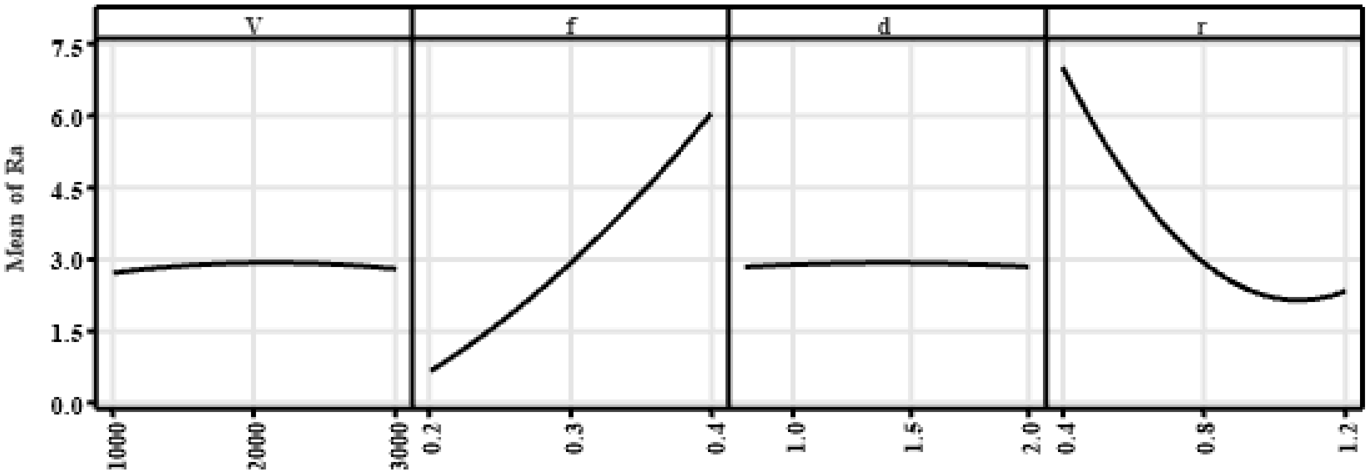

Figure 3: Main effect plot for surface roughness

4 Conclusion

The present study delves into the intricate dynamics of High-Speed Machining (HSM) of Aluminum 7075, offering valuable insights into the relationships between various process parameters and their effects on surface roughness. A key revelation of this research is the significant impact of the feed and nose radius on surface roughness, while cutting speed and depth of cut played secondary roles. These findings illuminate the complex interplay between process parameters in HSM of Aluminum 7075 alloy, forming a foundation for enhanced machining optimization strategies. This understanding is particularly valuable for industries reliant on aluminum components such as automotive, aerospace and electronics, as it offers avenues for improved manufacturing efficiency. Gaining precise control and optimization of machining processes through an understanding of parameter interactions leads to high-quality products, increased productivity and reduced operational costs. This research not only enriches the knowledge base on HSM of Aluminum 7075 but also opens avenues for future exploration. Uncharted areas for future research include the impacts of variables such as machine tool quality and type, vibrations, auxiliary tooling, and lubricants. Investigations into different aluminum alloys in comparison with Aluminum 7075 would also be an interesting extension of this work.

Declaration of Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

This research did not receive any grants from governmental, private, or nonprofit funding bodies.

Author Contribution

Deepak V Lokare: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Software, Writing - original draft, Writing - review and editing

References

[1] H. Reinecke, C. Müller, and S. Karazi, “Micromachining,” in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2016.

[2] F. Yang, K. Gao, I. W. Simon, Y. Zhu, and R. Su, “Decomposition methods for manufacturing system scheduling: a survey,” *IEEE/CAA Journal of Automatica Sinica*, vol. 5, pp. 389–400, mar 2018.

[3] V. P. Astakhov, “Turning,” in *Modern Machining Technology*, pp. 1–78, Elsevier, 2011.

[4] W. A. Knight and G. Boothroyd, *Fundamentals of Metal Machining and Machine Tools.* CRC Press, aug 2019.

[5] S. Mok, “Aluminum Economy for Sustainable Development: Aluminium as Core Material for Energy Storage and Energy Saving Products: Low Cost, High Performance, and Easy Processing in Developing Countries,” in *2011 IEEE Global Humanitarian Technology Conference*, pp. 21–24, IEEE, oct 2011.

[6] D. Flom, “High-Speed Machining of Metals,” *Annual Review of Materials Research*, vol. 14, pp. 231–278, jan 1984.

[7] Z. Q. Liu, Y. Wan, and X. Ai, “Recent Developments in Tool Materials for High Speed Machining,” *Materials Science Forum*, vol. 471-472, pp. 438–442, dec 2004.

[8] T. Ranjan Soren, R. Kumar, I. Panigrahi, A. Kumar Sahoo, A. Panda, and R. Kumar Das, “Machinability behavior of Aluminium Alloys: A Brief Study,” *Materials Today: Proceedings*, vol. 18, pp. 5069–5075, 2019.

[9] N. H. Ononiwu, E. T. Akinlabi, and C. G. Ozoegwu, “Optimization techniques applied to machinability studies for turning aluminium metal matrix composites: A literature review,” *Materials Today: Proceedings*, vol. 44, pp. 1124–1129, 2021.

[10] D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquère, V. Zerrouki, and J. Vigneau, “A review of developments towards dry and high speed machining of Inconel 718 alloy,” *International Journal of Machine Tools and Manufacture*, vol. 44, pp. 439–456, mar 2004.

[11] S. C. Cagan and B. B. Buldum, “Variants of high speed machining,” in *High Speed Machining*, pp. 283–302, Elsevier, 2020.

[12] B. Wang, Z. Liu, Q. Song, Y. Wan, and X. Ren, “A Modified Johnson–Cook Constitutive Model and Its Application to High Speed Machining of 7050-T7451 Aluminum Alloy,” *Journal of Manufacturing Science and Engineering*, vol. 141, jan 2019.

[13] R. A. Mali, M. D. Agrahari, and T. Gupta, “FE based simulation and experimental validation of forces in dry turning of aluminium 7075,” *Materials Today: Proceedings*, vol. 27, pp. 2319–2323, 2020.

[14] M. A. A. bin Abdullah, M. A. Muhammad, Z. Ibrahim, M. Y. Ali, and J. Purbolaksono, “Investigation of the turning parameters on the surface finish of an aluminum bar,” in *AIP Conference Proceedings*, vol. 2643, p. 050001, 2023.

[15] R. Abedinzadeh, E. Norouzi, and D. Toghraie, “Study on machining characteristics of SiC–Al2O3 reinforced aluminum hybrid nanocomposite in conventional and laser-assisted turning,” *Ceramics International*, vol. 48, pp. 29205–29216, oct 2022.

[16] A. Aswal, A. Jha, A. Tiwari, and Y. Modi, “CNC Turning Parameter Optimization for Surface Roughness of Aluminium-2014 Alloy Using Taguchi Methodology,” *Journal Européen des Systèmes Automatisés*, vol. 52, pp. 387–390, oct 2019.

[17] A. Abdallah, “Optimization of cutting parameters for surface roughness in CNC turning machining with aluminum alloy 6061 material,” *IOSR Journal of Engineering*, vol. 4, pp. 01–10, oct 2014.

[18] T. Sasimurugan and K. Palanikumar, “Analysis of the Machining Characteristics on Surface Roughness of a Hybrid Aluminium Metal Matrix Composite (Al6061-SiC-Al2O3),” *Journal of Minerals and Materials Characterization and Engineering*, vol. 10, no. 13, pp. 1213–1224, 2011.

[19] A. M. Pinar, “Optimization of Process Parameters with Minimum Surface Roughness in the Pocket Machining of AA5083 Aluminum Alloy via Taguchi Method,” *Arabian Journal for Science and Engineering*, vol. 38, pp. 705–714, mar 2013.

[20] S. T. Prashantha Kumara, H. P. Thirtha Prasada, N. M, and C. Siddaraju, “Investigate the effect of al2o3 & cuo nano cutting fluids under mql technique in turning of dss-2205,” *Advances in Materials and Processing Technologies*, vol. 8, pp. 3297–3330, Jul 2022.

[21] A. Samaila, R. Sankar, and A. I. Haruna, “Performance evaluation of mixture of groundnut oil and camel milk as cutting fluids on the surface of aluminium during turning,” *Materials Today: Proceedings*, jun 2023.

[22] M. Szymański, D. Przestacki, and P. Szymański, “Tool Wear and Surface Roughness in Turning of Metal Matrix Composite Built of Al2O3 Sinter Saturated by Aluminum Alloy in Vacuum Condition,” *Materials*, vol. 15, p. 8375, nov 2022.

[23] S. H. Musavi, M. Sepehrikia, B. Davoodi, and S. A. Niknam, “Performance analysis of developed micro-textured cutting tool in machining aluminum alloy 7075-T6: assessment of tool wear and surface roughness,” *The International Journal of Advanced Manufacturing Technology*, vol. 119, pp. 3343–3362, mar 2022.

[24] G. Struzikiewicz and A. Sioma, “Evaluation of Surface Roughness and Defect Formation after The Machining of Sintered Aluminum Alloy AlSi10Mg,” *Materials*, vol. 13, p. 1662, apr 2020.

[25] S. D. B. Menachery, N. T. and N. Senthilkumar, “Processing of nanoreinforced aluminium hybrid metal matrix composites and the effect of post-heat treatment: a review,” *Applied Nanoscience*, vol. 13, pp. 4075–4099, jun 2023.

[26] M. Imran and A. A. Khan, “Characterization of Al-7075 metal matrix composites: a review,” *Journal of Materials Research and Technology*, vol. 8, pp. 3347–3356, may 2019.

[27] M. N. Akhtar, T. Sathish, V. Mohanavel, A. Afzal, K. Arul, M. Ravichandran, I. A. Rahim, S. Alhady, E. A. Bakar, and B. Saleh, “Optimization of process parameters in cnc turning of aluminum 7075 alloy using l27 array-based taguchi method,” *Materials*, vol. 14, no. 16, p. 4470, 2021.

[28] B. Veluchamy, N. Karthikeyan, B. R. Krishnan, and C. M. Sundaram, “Surface roughness accuracy prediction in turning of al7075 by adaptive neuro-fuzzy inference system,” *Materials Today: Proceedings*, vol. 37, pp. 1356–1358, 2021.

[29] M. Lakshmanan, J. S. Rajadurai, and S. Rajakarunakaran, “Machining studies of al7075 in cnc turning using grey relational analysis,” *Materials Today: Proceedings*, vol. 39, pp. 1625–1628, 2021.

[30] B. Zhou, B. Liu, and S. Zhang, “The advancement of 7xxx series aluminum alloys for aircraft structures: A review,” *Metals*, vol. 11, p. 718, Apr 2021.

[31] C. Jawalkar and S. Kant, “A Review on use of Aluminium Alloys in Aircraft Components,” *i-manager’s Journal on Material Science*, vol. 3, pp. 33–38, dec 2015.

[32] E. Starke and J. Staley, “Application of modern aluminum alloys to aircraft,” *Progress in Aerospace Sciences*, vol. 32, no. 2-3, pp. 131–172, 1996.

[33] D. Ashkenazi, “How aluminum changed the world: A metallurgical revolution through technological and cultural perspectives,” *Technological Forecasting and Social Change*, vol. 143, pp. 101–113, jun 2019.

[34] P. G. Petropoulos, “The effect of feed rate and of tool nose radius on the roughness of oblique finish turned surfaces,” *Wear*, vol. 23, no. 3, pp. 299–310, 1973.

Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in
e-ISSN: 3009-075X

Volume 2 Issue 3

Article Number: 23065

Enhancing Voting Security and Efficiency: An Electronic Voting Machine (EVM) System Integrated With Biometric Identifiers

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Abstract

This study explores developing and implementing a novel Electronic Voting Machine (EVM) system integrated with biometric identifiers to enhance voting security and efficiency significantly. Traditionally, voting processes relied on paper ballots, a system fraught with several challenges, including over-voting, the loss or misplacement of ballot papers, environmental harm due to paper consumption, and a lengthy result compilation process. An advanced EVM system is proposed to address these issues, leveraging unique biometric identifiers - facial recognition and fingerprints - for voter authentication and secure vote recording. Our EVM system effectively improves the security against bogus voting and vote repetition, which have been significant concerns in previous voting systems. This robust approach to voter authentication minimizes the likelihood of voting fraud, thus contributing to a more reliable and secure voting process. However, the transition to this advanced EVM system is challenging. The study identifies key implications, including the impact on employment due to automation, potential inaccuracies and biases associated with biometric technologies, and vital privacy concerns surrounding using sensitive biometric data. Despite these challenges, the proposed system provides a substantial foundation for future enhancements. Opportunities for further development include the integration of additional biometric identifiers like iris recognition, refining the accuracy of current biometric technologies, and strengthening data privacy measures.

Keywords: Electronic Voting Machines; Biometric Identifiers; Voting Security; Facial Recognition; Fingerprint Authentication

1 Introduction

Voting, in its most fundamental sense, is a means to express choice or preference from an array of options. It forms the backbone of democratic processes worldwide, deciding the leaders the populace entrusts with power [1, 2]. This fundamental democratic process has undergone various transformations throughout history, from traditional paper ballots to more advanced Electronic voting machines (EVMs). However, the shift from traditional paper ballot voting to EVMs has not been without challenges and consequences [3–6]. Originally, the voting process involved the physical presence of each voter, the use of ballot papers, and manual counting – a method proven to be time-consuming and prone to inaccuracies and manipulation. Issues such as over-voting, where voters accidentally stamp more than once, and ballot papers being lost or miscalculated were significant challenges. These systemic problems, compounded with the environmental concerns around using paper, underscored the need for a more efficient and secure voting mechanism, hence the adoption of EVMs [4, 7, 8]. Designed and developed in India, in collaboration with Bharat Electronics Limited, Bangalore, and Electronics Corporation of India Limited, Hyderabad, EVMs promised to alleviate many of these challenges.

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Received: 06 July 2023; **Revised:** 14 July 2023; **Accepted:** 29 July 2023; **Published:** 31 August 2023

DOI: 10.57159/gadl.jcmm.2.3.23065.

Offering advantages such as efficient vote recording, quick result processing, enhanced voter-friendliness, and a reduction in the use of paper, EVMs marked a significant evolution in voting technology. However, adopting EVMs has also raised concerns [9–15]. The transition to an electronic voting system has reduced the need for manpower, potentially affecting employment during elections. Furthermore, questions about the security and integrity of the voting process in an electronic format remain. The present work aims to address these concerns and refine the current EVM system, utilizing biometric identifiers to strengthen security and integrity. By proposing the unique physical attributes of voters, such as facial recognition and fingerprint data, the study aims to establish an unhackable, accessible, and more reliable voting system. This paper details the methodology, discusses the outcomes and implications of the proposed system, and outlines future avenues for improving upon this novel application of biometric technology in voting systems.

2 Methods

The methodology of the proposed EVM system encompasses the use of biometric identifiers, namely facial recognition and fingerprint data, for enhanced security and reliability. The study aims to develop an unhackable voting system, reducing the instances of bogus voting and vote repetition.

2.1 Hardware and software requirements

The proposed EVM system requires the integration of specific hardware and software components. The hardware components included a fingerprint sensor for fingerprint-based authentication, an EVM controller, a global system for mobile communications (GSM) module, and a webcam for facial recognition. The chosen software for the proposed system was MATLAB 13 by MathWorks, which proved excellent in managing and processing biometric data [15, 16].

2.2 EVM architecture

The proposed EVM architecture comprises two main units - the ballot unit (BU) and the control unit (CU). The BU is operated by the voter and is placed in the election booth. It displays the voter's name, OTP, date, time, candidate party name, party symbols, submit buttons, and various buttons labeled with the party name. The CU, used by poll workers, is responsible for storing votes and controlling the polling process. Its functionalities are accessible only after a secure admin login, post which it offers access to the result of the voting, the EVM result, reset functions and the voter login panel. Figure 1 represents the block diagram of the proposed EVM architecture, illustrating the interaction between the BU and CU.

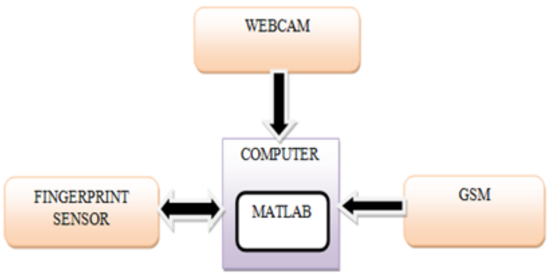

Figure 1: Block diagram of the proposed EVM architecture.

2.3 Biometric identifiers

The proposed EVM system leverages biometric identifiers for secure voter authentication. These identifiers are divided into two categories - physical and behavioral. The physical category includes face and fingerprint detection, while the behavioral category incorporates signature and voice detection. These identifiers provide a secure layer of verification, given their uniqueness to each individual [17–19]. In the proposed system, physical identifiers are used. The fingerprint detection technology uses the unique ridge and furrow patterns present on every individual's fingerprint [20, 21]. This uniqueness, coupled with the fact that fingerprints remain the same throughout an individual's life, makes them an effective tool for identification [22]. Figure 2 depicts a general fingerprint pattern that serves as a reliable biometric identifier. Face recognition, also known as automatic face recognition (AFR), uses the distinctive features of an individual's face for identification. This technology has advanced significantly and has numerous applications, such as personal identification and security systems [23, 24]. Combining these biometric technologies provides an enhanced security layer, facilitating a more secure and efficient voting process. However, it is worth noting that these technologies are not without their challenges and potential biases, which need to be continually addressed and improved upon to ensure an inclusive and accessible voting system.

Figure 2: A general fingerprint pattern of ridges and furrows.

3 Results

Figure 3: Flowchart of the proposed voting process

Implementing the proposed system resulted in marked improvements in security, efficiency and accessibility. Integrating biometric technologies with the EVM system enhanced the system's security against bogus voting and vote repetition. The system's process begins with the voter logging in. The voter is then prompted to enter their mobile and Aadhaar numbers, which must match the pre-stored information in the database. Once this step is completed, the system captures an image of the voter using the webcam. This image is then matched with the picture available in the database. Simultaneously, the voter's fingerprint is captured using the fingerprint sensor integrated into the EVM. The system matches this fingerprint with the data linked to the voter's Aadhaar number in the database. In cases where both image and fingerprint match the database records, the system generates a one-time password (OTP) sent to the voter's registered mobile number linked with their Aadhaar card. Following this, the voter enters the OTP, allowing them to cast their vote. Introducing fingerprint verification alongside facial recognition provides an additional layer of security to the voting process. It ensures a higher level of authenticity and prevents any potential identity fraud. Figure 3 depicts the flowchart of the proposed voting process, and Figure 4 represents the screen snapshot detailing each step from voter authentication to vote submission.

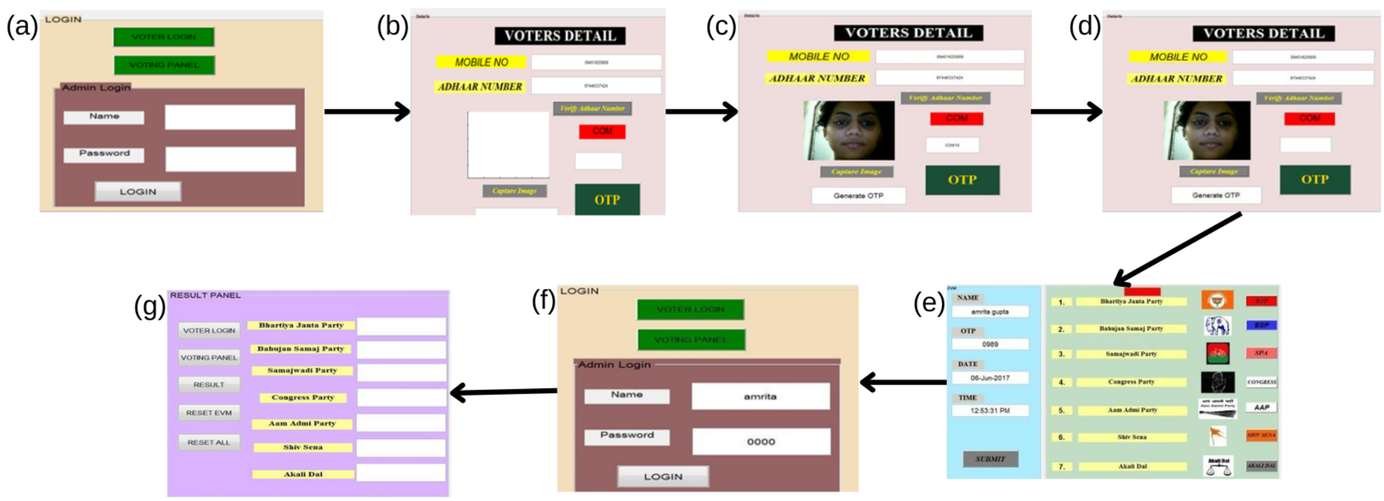

Figure 4: Flow process sequence: **(a)** Voter login interface; **(a)** Voter detail input page **(c)** Image capture and verification **(d)** COM Port Entry Stage **(e)** OTP verification and vote submission **(f)** Admin login stage **(g)** Result panel interface

Several key improvements became evident while comparing this implementation with the previous paper-based system:

- **Enhanced security**: Biometric identifiers substantially increased the voting process's security.
- **No misplacement**: Unlike ballot papers that could be lost or misplaced, votes can be securely stored in the EVM database.
- **Single-user single-vote**: The system ensures voters can vote only once, thus eliminating over-voting issues.
- **Accessibility for handicapped individuals**: The facial recognition feature allows physically challenged individuals to participate seamlessly in voting.
- **Efficiency**: The time consumed in the voting process can significantly reduce compared to the traditional ballot paper-based system.
- **Data recollection and recording**: The EVM system enables consistent and speedy recall and recording of voting data, which was not feasible with the previous system.

Regarding the EVM system's architecture, it was observed that the separation of functionalities into the BU and the Control CU streamlined the voting process. The BU, accessible to the voter, provided a user-friendly interface to cast their vote. Figure 5 depicts the proposed ballot unit having the user interface for the voter with the listed elements. The CU, operated by the poll workers, securely stored the votes and controlled the polling process. This architecture also allowed for real-time vote tallying, making the result compilation process faster and more efficient. Figure 6 represents the proposed control unit, highlighting the various functionalities available to the poll workers.

Figure 5: Proposed ballot unit.

Figure 6: Proposed control unit.

4 Discussion

The present work has primarily focused on enhancing the security and efficiency of the voting process by incorporating biometric technologies into the EVM system. Using unique biometric identifiers such as facial recognition and fingerprints has shown a substantial improvement in the system's security against vote repetition and false voting, two significant issues with previous voting methods. While the shift from traditional paper ballots to EVMs has reduced many systemic problems, including over-voting and lost ballot papers, it has brought forth its own challenges. One such concern revolves around the reduction of manpower. As EVMs automate many tasks previously performed by humans, employment is impacted during elections. This concern is substantial and needs to be addressed in the context of technological progress, where automation is often seen as a job killer. Potential solutions might involve the re-skilling of workers or their integration into different stages of the election process where human intervention is still essential.

Additionally, while biometric identifiers have improved the security and efficiency of the voting process, their use is not devoid of potential inaccuracies and biases. These technologies must be continually refined to prevent false rejections or acceptances and ensure they do not unfairly favor or disadvantage any particular group of voters. Privacy concerns must also be considered, as biometric data is sensitive personal information. Moreover, the proposed system's success hinges upon the matching of voter details with a pre-existing database, a process that may encounter discrepancies or mismatches. Safeguards must address situations where valid voters cannot match their details, ensuring they are not denied their fundamental right to vote. As the system stands now, it significantly improves the voting process's security and efficiency. However, given the continuous advancement in biometric technology and the existing room for improvement, future enhancements could include more robust security features and the integration of additional biometric identifiers like iris recognition for more secure polling. It is also important to consider the technical and infrastructural challenges that come with the implementation of such an advanced system. Not all regions or voting demographics may have equal access to the technology required for EVMs, potentially leading to disparities in voting accessibility. Future work must make the technology universally accessible, ensuring no voter is left behind in the shift toward a more advanced voting process.

5 Conclusion

The exploration and implementation of an electronic voting machine (EVM) system equipped with biometric identifiers have presented a new paradigm in the evolution of voting processes. The present work has shown that integrating unique biometric features like facial recognition and fingerprints into EVMs greatly enhances the system's security against bogus voting and vote repetition, thus making the voting process more reliable and secure. The adoption of EVMs has helped eliminate many of the issues associated with traditional paper-based systems, such as over-voting, loss of ballot papers, and environmental concerns around the use of paper. In addition, using EVMs has led to significant improvements in the efficiency of the voting process, with real-time vote tallying and quick result compilation. However, as we acknowledge the advancements and improvements made, we also recognize the challenges and implications this shift entails. Concerns over the impact on employment due to reduced manpower and potential discrepancies in voter database matching are significant and require further attention. Moreover, using biometric identifiers while enhancing security opens discussions around potential inaccuracies, biases, and privacy concerns. Looking forward, the system presents considerable scope for further enhancement. Security could be bolstered through more robust measures and the integration of additional biometric identifiers, such as iris recognition.

Efforts should also focus on addressing the employment concerns raised by the adoption of EVMs and ensuring the universal accessibility of the technology, irrespective of regional or demographic disparities. In conclusion, while the proposed EVM system offers a substantial leap in the right direction, it is a continuous process of evolution and improvement to meet emerging challenges and ensure a secure, efficient, and inclusive voting process.

Declaration of Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

This research did not receive any grants from governmental, private, or nonprofit funding bodies.

Author Contribution

Nikhil Ranjan: Conceptualization, Methodology, Investigation, Visualization, Software, Writing - original draft, Writing - review and editing.

References

[1] M. Khosla, "The possibility of modern India," *Global Intellectual History*, 2021.

[2] A. Shah, "What if We Selected our Leaders by Lottery? Democracy by Sortition, Liberal Elections and Communist Revolutionaries," *Development and Change*, vol. 52, no. 4, pp. 687–728, 2021.

[3] A. Kud, "Decentralized Information Platforms in Public Governance: Reconstruction of the Modern Democracy or Comfort Blinding?," *International Journal of Public Administration*, vol. 46, no. 3, pp. 195–221, 2023.

[4] D. Pawade, A. Sakhapara, A. Badgujar, D. Adepu, and M. Andrade, "Secure Online Voting System Using Biometric and Blockchain," *Advances in Intelligent Systems and Computing*, vol. 1042, pp. 93–110, 2020.

[5] T. M. A. Elven and S. A. Al-Muqorrobin, "Consolidating Indonesia's Fragile Elections Through E-Voting: Lessons Learned from India and the Philippines," *Indonesian Comparative Law Review*, vol. 3, no. 1, pp. 63–80, 2021.

[6] S. Agarwal, A. Haider, A. Jamwal, P. Dev, and R. Chandel, "Biometric based secured remote electronic voting system," *2020 7th International Conference on Smart Structures and Systems, ICSSS 2020*, 2020.

[7] A. Olumide, B. Olutayo, and S. Adekunle, "A Review of Electronic Voting Systems: Strategy for a Novel," *International Journal of Information Engineering and Electronic Business*, vol. 12, no. 1, pp. 19–29, 2020.

[8] A. K. Tyagi, T. F. Fernandez, and S. U. Aswathy, "Blockchain and Aadhaar based Electronic Voting System," *Proceedings of the 4th International Conference on Electronics, Communication and Aerospace Technology, ICECA 2020*, pp. 498–504, 2020.

[9] A. Shankar, P. Pandiaraja, K. Sumathi, T. Stephan, and P. Sharma, “Privacy preserving E-voting cloud system based on ID based encryption,” *Peer-to-Peer Networking and Applications*, vol. 14, pp. 2399–2409, jul 2021.

[10] S. Risnanto, Y. B. A. Rahim, N. S. Herman, and A. Abdurrohman, “E-Voting readiness mapping for general election implementation,” *Journal of Theoretical and Applied Information Technology*, vol. 98, no. 20, pp. 3280–3290, 2020.

[11] Z. Desai and A. Lee, “Technology and protest: the political effects of electronic voting in India,” *Political Science Research and Methods*, vol. 9, pp. 398–413, apr 2021.

[12] Y. B. Hamdan and A. Sathesh, “Construction of Efficient Smart Voting Machine with Liveness Detection Module,” *Journal of Innovative Image Processing*, vol. 3, no. 3, pp. 255–268, 2021.

[13] A. C. Sheela and G. F. Ramya, “E-voting system using homomorphic encryption technique,” *Journal of Physics: Conference Series*, vol. 1770, no. 1, 2021.

[14] I. Arora, “Election Commission of India: Institutionalising Democratic Uncertainties,” *Asian Affairs*, vol. 52, no. 1, pp. 228–230, 2021.

[15] K. A. Alnajjar and O. Hegy, “Attendance System Based on Biometrics and RFID,” in *2019 Fifth International Conference on Image Information Processing (ICIIP)*, vol. 2019-Novem, pp. 596–599, IEEE, nov 2019.

[16] S. Jabin, S. Ahmad, S. Mishra, and F. J. Zareen, “iSignDB: A database for smartphone signature biometrics,” *Data in Brief*, vol. 33, p. 106597, dec 2020.

[17] J. Mason, R. Dave, P. Chatterjee, I. Graham-Allen, A. Esterline, and K. Roy, “An Investigation of Biometric Authentication in the Healthcare Environment,” *Array*, vol. 8, p. 100042, dec 2020.

[18] S. M. J. Amali, M. D. C., and R. G., “Evolution of Deep Learning for Biometric Identification and Recognition,” in *Handbook of Research on Computer Vision and Image Processing in the Deep Learning Era*, pp. 147–160, oct 2022.

[19] S. Dargan and M. Kumar, “A comprehensive survey on the biometric recognition systems based on physiological and behavioral modalities,” *Expert Systems with Applications*, vol. 143, p. 113114, apr 2020.

[20] M. A. Bhimrao and B. Gupta, “An empirical study of dermatoglyphics fingerprint pattern classification for human behavior analysis,” *Social Network Analysis and Mining*, vol. 13, p. 79, apr 2023.

[21] J. K. Appati, P. K. Nartey, E. Owusu, and I. W. Denwar, “Implementation of a Transform-Minutiae Fusion-Based Model for Fingerprint Recognition,” *International Journal of Mathematics and Mathematical Sciences*, vol. 2021, pp. 1–12, mar 2021.

[22] N. Kaushal and P. Kaushal, “Human Identification and Fingerprints: A Review,” *Journal of Biometrics and Biostatistics*, vol. 02, no. 04, 2011.

[23] R. S. Ghiass, O. Arandjelovic, H. Bendada, and X. Maldague, “Infrared face recognition: A literature review,” in *The 2013 International Joint Conference on Neural Networks (IJCNN)*, pp. 1–10, IEEE, aug 2013.

[24] Y. Kortli, M. Jridi, A. Al Falou, and M. Atri, “Face Recognition Systems: A Survey,” *Sensors*, vol. 20, p. 342, jan 2020.

Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in
e-ISSN: 3009-075X
AAN PUBLISHING

Volume 2 Issue 3

Article Number: 23062

Optimizing Space Utilization In Container Packing: A Comparative Analysis of Packing Algorithms

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Abstract

Container packing presents a complex optimization problem that seeks to efficiently pack diverse items into a fixed-size container. This study provides a comparative analysis of four algorithms – Greedy Shelf, Shelfing with Rotation, Shelfing with Search, and Guillotine Paper Cutting – investigating their proficiency in solving the container packing problem. Utilizing a set of four packages with differing dimensions and IDs, The study evaluated the performance of each algorithm. The results demonstrated that the Shelfing with Search algorithm outperformed its counterparts by yielding a stack height of 3019610 L units. Conversely, the Guillotine Paper Cutting algorithm performed poorly, with a stack height of 7537295 units. This research also explored the impact of different sorting methods on packing efficiency, revealing that sorting packages in descending order of height yields superior results. Consequently, this study provides an extensive evaluation of the various algorithms used for container packing, while suggesting promising directions for future research to enhance packing efficiency.

Keywords: Container Packing Problem; Optimization; Shelfing With Rotation; Shelfing With Search; Guillotine Algorithm

1 Introduction

Container packing is a significant and complex optimization problem that has substantial implications in logistics and supply chain management, necessitating efficient solutions [1, 2]. It involves packing cuboid-shaped containers into a given space, with the dual aims of maximizing space utilization and minimizing the number of containers used [3–5]. In real-world terms, effective container packing can translate into tangible benefits, including reducing logistics costs, decreasing environmental impact, and increasing productivity [6]. Examples of these benefits can be seen in everyday operations of shipping companies and warehouses, where optimal container packing can reduce loading and unloading times, minimize transportation costs, and prevent port congestion [7–9]. Furthermore, containerization, the use of standard intermodal containers, has dramatically transformed international commerce by enabling efficient long-distance goods transportation [10, 11]. Yet, due to product variability and limited space, optimal container packing remains a significant challenge [12]. The present work addresses the bin packing problem, wherein the goal is to pack either a single container as densely as possible or use as few containers as possible to pack all objects [13]. The study devises and compares various algorithms aimed at maximizing the use of available space within containers. The remainder of this article provides a detailed account of the problem statement, the data generation and algorithm development methodologies, and the results obtained from the evaluation of various algorithms. Each algorithm's effectiveness is assessed through a comparison of their pseudocodes. The study also present a thorough discussion of the findings, potential limitations, and suggestions for future research.

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Received: 14 June 2023; **Revised:** 20 July 2023; **Accepted:** 29 July 2023; **Published:** 31 August 2023

DOI: 10.57159/gadl.jcmm.2.3.23062.

2 Related Work

Substantial research has been conducted on the container packing problem, resulting in the development of various algorithms, each offering unique strengths and limitations [14–16]. This section reviews some of these algorithms, as shown in Table 1, and their applications to the container packing problem, setting the stage for the current study's objectives and methods.

Table 1: Summary of Various Algorithms for the Container Packing Problem

Algorithm	Strengths	Weaknesses
Next-Fit Decreasing Algorithm	Simple and efficient to implement [14–16]	Does not always produce optimal results [17]
Best-Fit Algorithm	Yields more optimal results than the Next-Fit Algorithm [18]	Computationally complex [19]
Shelf Algorithms	Various iterations have been developed, offering flexible solutions [20]	Some versions may not optimally utilize the available space [21]
Genetic Algorithm	Uses evolutionary principles to find optimal packing solutions [22]	Complexity and computational requirements can be high [22]
Simulated Annealing Algorithm	Mimics the process of annealing in metallurgy to search for the best packing solution [23]	Could be computationally expensive and results are not always consistent [23]

As shown in Table 1, each algorithm presents unique advantages but also exhibits certain limitations. Therefore, the quest for comprehensive solutions to the container packing problem continues, emphasizing the importance and relevance of the present study.

3 Problem Statement

The focus of this study is to develop and compare algorithms for the optimal packing of one million cuboid-shaped packages into a container with a base area of 1000L by 1000L units, where L denotes the basic unit length. The packages must be packed following decreasing order of their ID, without any overlapping. Although packages can be oriented in any direction parallel to the x, y, or z axes (i.e., they can be rotated in multiples of 90 degrees), the constraint lies in maximizing the density of packing and minimizing the number of containers utilized. The problem statement includes several constraints and requirements to emulate real-world conditions. Although there is no limitation on the stack height, the base area of the stack must not exceed 1000 by 1000 units. Additionally, the packing order must be strictly maintained, and package dimensions are interchangeable, given the 90-degree rotation constraint around the x, y, or z axes. Backtracking is not permitted, eliminating the possibility of repacking for optimization once a package has been placed. The motivation behind this problem lies in its practical implications. Consider a scenario where a shipping company needs to transport a large number of packages of varying sizes across the globe. Inefficient packing could lead to higher costs, more containers used, and increased environmental impact due to the larger number of shipments. Hence, optimizing the packing process can provide significant economic and environmental benefits, making it a crucial concern for industries involved in shipping, transportation, and warehousing. This problem is not just an academic exercise, but it also addresses a key logistical challenge faced by industries globally. A successful solution could pave the way for the development of robust, general-purpose packing algorithms for a variety of applications, emphasizing the significance and relevance of the current study.

4 Methodology

The approach in the present study to solving the container packing problem involved two primary steps: data generation and algorithm development.

4.1 Data Generation

Python scripting language was used to generate random numbers within the range of 1 to 250. These random numbers represent the dimensions of the packages. The dimensions, along with the package ID, were stored in a CSV file for further processing.

4.2 Algorithm Development

The algorithm development phase involved the comparison and evaluation of four algorithms to determine their effectiveness in packing the cuboid-shaped packages into the container. The algorithms under investigation were the Basic Greedy Shelf algorithm, the Shelfing with Rotation algorithm, the Shelfing with Internal Search algorithm, and the Guillotine Paper Cutting algorithm. Unlike previous methods, our methodology differs in two significant aspects.

Firstly, the Python scripting language was leveraged for data generation, which helped in creating a large dataset of packages that align with the problem requirements. Secondly, based our evaluation of the algorithms on the height of the stack formed by packing the packages within the provided space, provided a more objective measure for comparing the effectiveness of the algorithms.

5 Algorithms

Four distinct algorithms were examined for resolving the container packing problem: the Basic Greedy Shelf (BGS) algorithm, the Shelfing with Rotation (SwR) algorithm, the Shelfing with Internal Search (SwIS) algorithm, and the Guillotine Paper Cutting (GPC) algorithm. Each algorithm is described below, accompanied by pseudocode and examples.

5.1 Basic Greedy Shelf Algorithm

The BGS algorithm, as a simple yet effective heuristic, commences the packing process from the origin and continues by adding packages along the x-axis (lengthwise). When the end of a shelf is reached, the algorithm moves up to the next level. This process continues until the height limit of the container is reached. The algorithm can be summarised as listing 1.

Listing 1: Pseudocode for Basic Greedy Shelf algorithm

```
def basic_greedy_shelf(packages):
cursor = (0,0,0) # initialize cursor at the origin
for p in packages:
if can_add_to_current_shelf(p, cursor):
add_to_shelf(p, cursor)
cursor = (cursor[0] + p.width, cursor[1], cursor[2])
else:
cursor = (0, get_max_height_of_previous_shelf(), cursor[2])
add_to_shelf(p, cursor)
```

5.2 Shelfing with Rotation Algorithm

The SwR algorithm extends the BGS algorithm by incorporating the rotation of packages, ensuring that the package's height does not exceed the level height or shelf height. The pseudocode for the SwR algorithm is given in Listing 2.

Listing 2: Pseudocode for Shelfing with Rotation algorithm

```
def shelfing_with_rotation(packages):
cursor = (0,0,0)
for p in packages:
if can_add_to_current_shelf(p, cursor):
add_to_shelf(p, cursor)
cursor = (cursor[0] + p.width, cursor[1], cursor[2])
else:
p.rotate_to_best_fit() # rotate package for optimal fit
if can_add_to_current_shelf(p, cursor):
add_to_shelf(p, cursor)
cursor = (cursor[0] + p.width, cursor[1], cursor[2])
else:
cursor = (0, get_max_height_of_previous_shelf(), cursor[2])
add_to_shelf(p, cursor)
```

5.3 Shelfing with Internal Search Algorithm

The SwIS algorithm further enhances the SwR algorithm by keeping track of packages packed in the z-direction. The algorithm scans for a gap in the current shelf where the package can fit, optimizing the utilization of space. The pseudocode for the SwIS algorithm is given in Listing 3.

5.4 Guillotine Paper Cutting Algorithm

The GPC algorithm adopts a recursive approach to divide the container space into filled and unfilled regions. It handles irregularly shaped packages by repeatedly dividing the container space, ensuring high space utilization. Despite its robustness, it can be computationally intensive, especially when dealing with a large number of packages. The pseudocode for the GPC algorithm is is given in Listing 4.

Listing 3: Pseudocode for Shelfing with Internal Search algorithm

```
def shelfing_with_internal_search(packages):
cursor = (0,0,0)
for p in packages:
if can_add_to_current_shelf(p, cursor):
add_to_shelf(p, cursor)
cursor = (cursor[0] + p.width, cursor[1], cursor[2])
else:
margin = find_margin_in_current_shelf(p)
if margin:
add_to_shelf_at_margin(p, margin)
else:
cursor = (0, get_max_height_of_previous_shelf(), cursor[2])
add_to_shelf(p, cursor)
```

Listing 4: Pseudocode for Guillotine Paper Cutting algorithm

```
def guillotine_paper_cutting(packages):
container = Container()
while packages:
p = select_largest_package(packages)
space = find_best_space(p, container)
if space:
place_in_space(p, space)
else:
p.rotate_to_best_fit()
space = find_best_space(p, container)
if space:
place_in_space(p, space)
else:
smaller_spaces = cut_space(space)
guillotine_paper_cutting(smaller_spaces)
return container
```

6 Data Generation and Algorithm Evaluation

6.1 Python code for data generation

The Python code below generates a list of a predefined number of cuboid-shaped packages. Each package is randomly assigned dimensions between 50L and 200L. These packages are represented as objects of the *Package* class, each with a length, width, height, and package ID. The *Package* class also includes a *rotate* method, which allows for the rotation of the package by 90 degrees, thus facilitating packing in various orientations.

```
import random
class Package:
def __init__(self, length, width, height, package_id):
self.length = length
self.width = width
```

```
self.height = height
self.package_id = package_id
def rotate(self):
# Rotate package by 90 degrees
self.length, self.width = self.width, self.length
def __str__(self):
return f'Package {self.package_id}: {self.length}L x {self.width}L x {self.height}L'
def generate_data(num_packages):
packages = []
for i in range(num_packages):
length = random.randint(50, 200)
width = random.randint(50, 200)
height = random.randint(50, 200)
packages.append(Package(length, width, height, i+1))
return packages
```

6.2 Python code for algorithm evaluation

The provided Python code can be used to evaluate the height of the stack created by various packing algorithms for a given set of packages. The *pack_packages* function is designed to accept a list of packages and a packing algorithm, subsequently returning a list of packed packages along with their respective coordinates. The *calculate_stack_height* function takes this list of packed packages and computes the maximum height of the stack. This combined usage enables us to evaluate the stack height resultant from our algorithm choices.

```
def pack_packages(packages, algorithm):
# Implement the selected packing algorithm here
# and return a list of packed packages with their coordinates
def calculate_stack_height(packed_packages):
max_height = 0
for package in packed_packages:
if package[3] > max_height:
max_height = package[3]
return max_height

# Example usage
packages = [(1, 200, 100, 50), (2, 100, 100, 50), (3, 50, 50, 50), (4, 50, 50, 50)]
packed_packages = pack_packages(packages, 'Shelfing with Rotation')
stack_height = calculate_stack_height(packed_packages)
print("Stack height:", stack_height)
```

7 Results and Discussion

This study compared the performance of four algorithms for solving the container packing problem: the Greedy Shelf algorithm, Shelfing with Rotation, Shelfing with Search, and the Guillotine Paper Cutting algorithm. The efficacy of each algorithm was gauged on the basis of the height of the resulting stack. Table 2 provides a comparative analysis of the effects of different sorting methods on the input packages.

Table 2: Comparison of various sorting methods and their effects

Sorting Method	Area Usage %	Did Not Fit
Height	90	NA
Width	88	40x50, 40x50, 40x50
Random	66	100x200, 250x80, 100x200, 40x50

In the case where packages were organized in descending order based on their height, area utilization was roughly 90% of the total available area. However, random arrangement led to a decrease in area utilization, amounting to around 65% of the total area. Width-based sorting resulted in 88% area utilization, with some packages not fitting into the area. Among the algorithms compared, the Greedy Shelf algorithm yielded a stack of height 5270836 L units, while Shelfing with Rotation and Shelfing with Search resulted in stacks of height 3929432 L and 3019610 L units, respectively.

Notably, the Guillotine Paper Cutting algorithm produced the highest stack, with a height of 7537295 L units. From these observations, it is clear that the Shelfing with Search algorithm outperforms both the Greedy Shelf algorithm and the Shelfing with Rotation algorithm. It resulted in approximately a 40% reduction in stack height compared to the former two. Contrary to expectations, the Guillotine Paper Cutting algorithm showed inferior performance when compared to the other three algorithms. Figures 1 and 2 illustrate the placement of packages for the cases of random order and descending order based on height, respectively. The former case achieved roughly 65% area utilization, while the latter resulted in 90% utilization. From these findings, it can be concluded that the Shelfing with Search algorithm is the most effective solution for the container packing problem among the tested algorithms. Future studies could focus on exploring variations of the Shelfing with Search algorithm, such as incorporating different heuristics or optimizing for other metrics. Figures 1, 2, and 3 along with Table 2 serve as a strong visual support to this discussion, illustrating the efficacy of various sorting methods and algorithms.

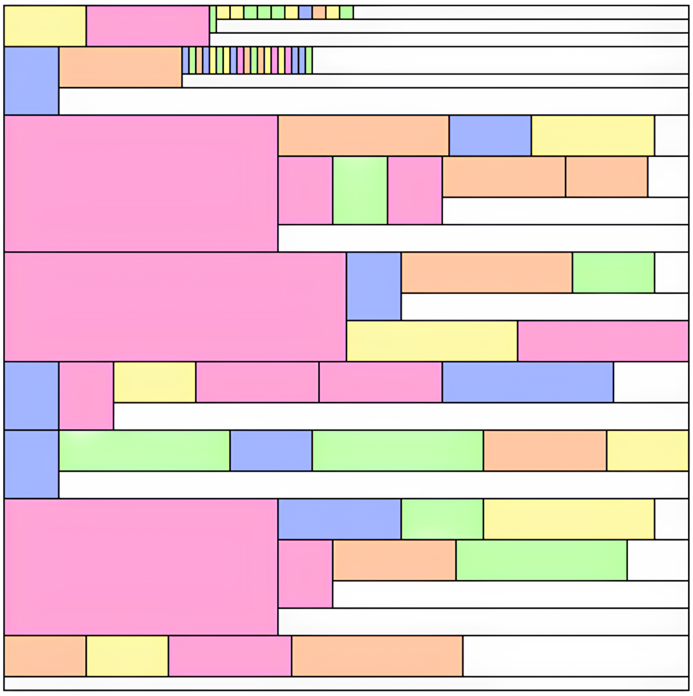

Figure 1: Random order placement: An illustration of package arrangement.

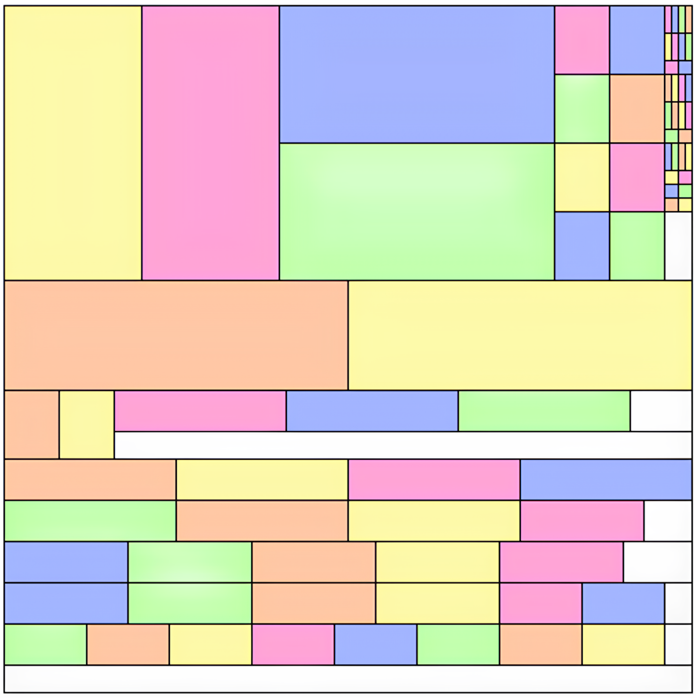

Figure 2: Decreasing height order placement: An effective strategy for container packing

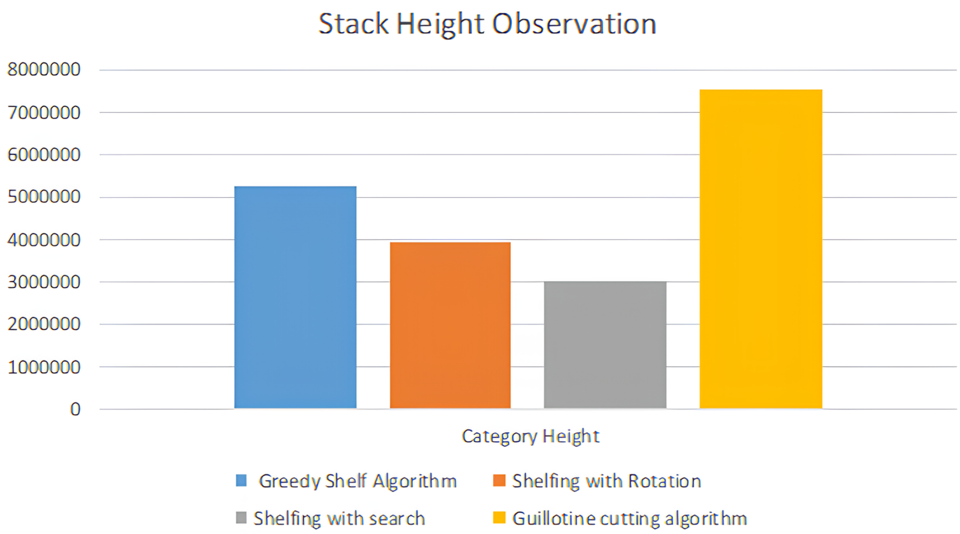

Figure 3: Comparison of stack heights: Observing the efficacy of different algorithms.

8 Conclusion

This research set out to explore various algorithms to tackle the container packing problem, a complex problem that involves packing cuboid-shaped containers under a variety of constraints. Three algorithms – Shelfing with Rotation, Shelfing with Internal Search, and Guillotine Paper Cutting – were investigated in this study, their performance evaluated by packing containers of randomly generated dimensions into a container of fixed size. The results of the study demonstrate that the Shelfing with Internal Search algorithm performed the most effectively, resulting in the lowest average height of the packed containers. Shelfing with Rotation also showed commendable performance, while Guillotine Paper Cutting, despite its common use, had the highest average height and fell short when compared to the other two algorithms. The implications of this research extend to the shipping industry, where efficient use of container space has direct consequences for cost-effectiveness. By offering insights into the efficacy of various algorithms in solving the container packing problem, this study stands to assist shipping companies in optimizing their packing processes. However, certain limitations do apply to this study, notably the use of randomly generated package dimensions and a fixed container size, which may not accurately reflect the complexity of real-world scenarios. For future research, it would be beneficial to explore the performance of these algorithms under different constraints and with a broader spectrum of package sizes and shapes. Additionally, advancements in technology offer intriguing possibilities for further investigation. Specifically, the exploration of machine learning algorithms to solve the container packing problem may yield promising results and provide a more nuanced understanding of this problem.

Declaration of Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

This research did not receive any grants from governmental, private, or nonprofit funding bodies.

Author Contribution

C. Raghavendra Kamath: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Software, Writing - original draft, Writing - review and editing

References

[1] G. Yaskov, T. Romanova, I. Litvinchev, and S. Shekhovtsov, “Optimal packing problems: from knapsack problem to open dimension problem,” in *International Conference on Intelligent Computing & Optimization*, pp. 671–678, Springer, 2019.

[2] J.-L. Lin, C.-H. Chang, and J.-Y. Yang, “A study of optimal system for multiple-constraint multiple-container packing problems,” in *International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems*, pp. 1200–1210, Springer, 2006.

[3] Y.-B. Shin and E. Kita, “Solving two-dimensional packing problem using particle swarm optimization,” *Computer Assisted Methods in Engineering and Science*, vol. 19, no. 3, pp. 241–255, 2017.

[4] T. G. Crainic, G. Perboli, and R. Tadei, “Extreme point-based heuristics for three-dimensional bin packing,” *Informs Journal on computing*, vol. 20, no. 3, pp. 368–384, 2008.

[5] S. Erbayrak, V. Özkır, and U. M. Yıldırım, “Multi-objective 3d bin packing problem with load balance and product family concerns,” *Computers & Industrial Engineering*, vol. 159, p. 107518, 2021.

[6] H. Pålsson, *Packaging Logistics: Understanding and managing the economic and environmental impacts of packaging in supply chains*. Kogan Page Publishers, 2018.

[7] C. A. Vega-Mejía, J. R. Montoya-Torres, and S. M. Islam, “Consideration of triple bottom line objectives for sustainability in the optimization of vehicle routing and loading operations: a systematic literature review,” *Annals of Operations Research*, vol. 273, pp. 311–375, 2019.

[8] C. Bierwirth and F. Meisel, “A follow-up survey of berth allocation and quay crane scheduling problems in container terminals,” *European Journal of Operational Research*, vol. 244, no. 3, pp. 675–689, 2015.

[9] N. Tsolakis, D. Zissis, S. Papaefthimiou, and N. Korfiatis, “Towards ai driven environmental sustainability: an application of automated logistics in container port terminals,” *International Journal of Production Research*, vol. 60, no. 14, pp. 4508–4528, 2022.

[10] E. Sdoukopoulos and M. Boile, “Port-hinterland concept evolution: A critical review,” *Journal of Transport Geography*, vol. 86, p. 102775, 2020.

[11] S. Nurosidah, “The shift of containerisation influence: 50-year logistics innovation in international business,” *The Business & Management Review*, vol. 8, no. 4, p. 93, 2017.

[12] L. Kroon and G. Vrijens, “Returnable containers: an example of reverse logistics,” *International journal of physical distribution & logistics management*, vol. 25, no. 2, pp. 56–68, 1995.

[13] M. Hifi, R. M’hallah, *et al.*, “A literature review on circle and sphere packing problems: Models and methodologies,” *Advances in Operations Research*, vol. 2009, 2009.

[14] S. Kumaraswamy and M. K. Nair, “Bin packing algorithms for virtual machine placement in cloud computing: a review,” *International Journal of Electrical and Computer Engineering*, vol. 9, no. 1, p. 512, 2019.

[15] A. Lodi, S. Martello, M. Monaci, and D. Vigo, “Two-dimensional bin packing problems,” *Paradigms of combinatorial optimization: Problems and new approaches*, pp. 107–129, 2014.

[16] A. Lodi, S. Martello, and D. Vigo, “Recent advances on two-dimensional bin packing problems,” *Discrete Applied Mathematics*, vol. 123, no. 1-3, pp. 379–396, 2002.

[17] D. Pisinger, “Heuristics for the container loading problem,” *European journal of operational research*, vol. 141, no. 2, pp. 382–392, 2002.

[18] S. Sweep, “Three dimensional bin-packing issues and solutions,” 2003.

[19] P. Ramanan, “Average-case analysis of the smart next fit algorithm,” *Information processing letters*, vol. 31, no. 5, pp. 221–225, 1989.

[20] A. Lodi, S. Martello, and D. Vigo, “Heuristic and metaheuristic approaches for a class of two-dimensional bin packing problems,” *Informs journal on computing*, vol. 11, no. 4, pp. 345–357, 1999.

[21] A. Lodi, S. Martello, and D. Vigo, “Neighborhood search algorithm for the guillotine non-oriented two-dimensional bin packing problem,” *Meta-heuristics: advances and trends in local search paradigms for optimization*, pp. 125–139, 1999.

[22] B. S. Baker and J. S. Schwarz, “Shelf algorithms for two-dimensional packing problems,” *SIAM Journal on Computing*, vol. 12, no. 3, pp. 508–525, 1983.

[23] K. A. Dowsland, “Some experiments with simulated annealing techniques for packing problems,” *European Journal of Operational Research*, vol. 68, no. 3, pp. 389–399, 1993.

Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in
e-ISSN: 3009-075X

Volume 2 Issue 3

Article Number: 23080

Service Quality and Customer Satisfaction in Rural Public Sector Banks: An Empirical Analysis in Lucknow District, Uttar Pradesh, India

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Abstract

In the rapidly evolving banking sector, understanding the relationship between service quality and customer satisfaction, particularly in rural public sector banks, is crucial. This research focuses on selected rural public sector banks in Lucknow District, Uttar Pradesh, India, investigating the dimensions of service quality and their impact on customer satisfaction. The study employs a quantitative research design, utilizing the SERVQUAL model for data collection and statistical analysis. Findings reveal that dimensions such as Tangibility, Reliability, Responsiveness and Empathy significantly influence customer satisfaction, with variations in their effects. The research highlights the importance of enhancing specific service quality factors to improve overall customer satisfaction and provides valuable insights for the rural banking sector. The study's outcomes shall guide targeted efforts in policy formulation, thereby contributing to the sustainable development of rural communities through enhanced public sector banking services.

Keywords: Rural Banking; Service Quality; Customer Satisfaction; SERVQUAL; Empirical Study

1 Introduction

In the dynamic and competitive world of banking, service quality and customer satisfaction stand out as vital determinants of success, particularly in public sector banks serving rural communities [1, 2]. The interplay between these factors not only fosters financial inclusion but also fuels rural economic growth. Especially in India's populous state of Uttar Pradesh, India, where rural areas present untapped economic potential, public sector banks play a critical role [3]. Despite substantial research confirming the positive relationship between service quality and customer satisfaction in urban settings [4, 5], a significant gap exists in understanding this relationship within rural banking. This study aims to fill this void by exploring the dynamics of service quality in public rural sector banks [6] in Lucknow District, Uttar Pradesh. It seeks to assess how service quality influences customer satisfaction, focusing on aspects such as reliability, responsiveness and customization. Through a mixed-methods approach, combining quantitative and qualitative techniques [7], this research will investigate selected public rural sector banks in Lucknow District. By evaluating service quality and its effect on customer satisfaction, the study intends to offer tailored strategies to meet rural bank customers' unique needs. Insights into the challenges faced in delivering quality services will also be illuminated. The objectives of the research encompass studying the relevance of tangibility in enhancing customer satisfaction; exploring the impact of reliability, responsiveness, and assurance on satisfaction; and investigating the influence of empathy on customer satisfaction.

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Received: 29 July 2023; **Revised:** 07 August 2023;**Accepted:** 09 August 2023; **Published:** 31 August 2023

DOI: 10.57159/gadl.jcmm.2.3.23080.

These objectives collectively frame the study's inquiry into the complex factors affecting satisfaction in the banking sector. The findings are expected to enrich the existing literature on service quality and customer satisfaction in rural banking, guiding bank managers and policymakers in targeted efforts to improve service quality and customer satisfaction. Ultimately, this research targets to contribute to the sustainable development of rural communities through the enhancement of public sector banking services.

2 Related Work

Numerous research contributions have established a positive correlation between service quality and customer satisfaction in the banking sector [8–11]. Parasuraman, Zeithaml, and Berry's seminal SERVQUAL model (1985) [12] emphasized five dimensions of service quality: Tangibility, Reliability, Responsiveness, Assurance, and Empathy. These dimensions have been widely adopted and adapted to evaluate service quality across various banking environments, including public sector banks. Service quality extends its influence beyond customer satisfaction to customer loyalty and advocacy. Satisfied customers are likely to become loyal supporters of a bank and endorse it to others [13]. Building customer loyalty is essential for public sector banks to maintain competitiveness and guarantee long-term profitability [14]. Reichheld and Sasser's research (1990) accentuated the crucial role of service quality in customer retention [15]. Elevated levels of service quality lead to reduced customer turnover and attrition rates, resulting in a more steadfast customer base [16]. In the public domain, where trust is paramount, retaining customers through superior service quality becomes even more vital. Tangibility, the physical attributes of service delivery, significantly affects customer perceptions. Studies indicate that thoughtfully designed branches and professional staff can positively influence customer satisfaction and brand perception[17]. Public sector banks may utilize this knowledge to improve the tangible aspects of their service delivery. Furthermore, responsiveness, comprising rapid issue resolution and prompt customer service, is instrumental in shaping customer experiences [18]. Efficient and competent responses to customer inquiries can markedly affect satisfaction and the overall perception of the bank's service quality. Likewise, empathy, characterized by personalized attention and understanding of customers' needs, emerges as a key determinant in customer satisfaction [19]. Empathetic interactions may foster emotional connections, engendering loyalty and trust. This aspect of customer relationship management is particularly pertinent for public sector banks aiming to establish enduring connections with their clients. The works of Omoregie et. al (2019) [20], Rabbani et. al (2020) [21], and Egala et. al (2021) [22] focus on various facets of customer retention, marketing strategies, and challenges in the Indian banking industry. They collectively highlight the strategies and understandings essential for customer retention and satisfaction, especially in the context of public banks. The literature review accentuates the supreme importance of service quality in public sector banks and its direct impact on customer satisfaction, loyalty, and retention. The critical dimensions of Tangibility, Reliability, Responsiveness, Assurance, and Empathy profoundly influence customer perceptions and experiences. By understanding these aspects, public sector banks in Lucknow District, Uttar Pradesh, can identify areas for improvement and formulate strategies to enhance customer satisfaction. Such understanding paves the way for building lasting relationships with their customers. In light of the insights derived from existing studies, future research in this area should explore the unique challenges and opportunities faced by public sector banks in rural areas. Investigating these aspects could yield customized strategies for boosting service quality and customer satisfaction, catering to the specific needs of this distinct context. Pursuing these research directions can contribute significantly to the enhancement of banking services in rural regions, promoting financial inclusivity, and laying a foundation for sustainable community growth and development.

3 Method

This section delineates the research methodology employed in the present study. The methodology elucidates the systematic approach and techniques utilized to collect, analyze, and interpret data, thereby addressing the research objectives and answering the pertinent research questions. The core aim of the study is to investigate the relationship between service quality and customer satisfaction, focusing on selected rural sector banks within Lucknow District, Uttar Pradesh. A summary of the research methodology used in the present study is given in Table 1

3.1 Scope and Research Design

The scope of the study and its coverage area is limited to the Lucknow district, Uttar Pradesh, India, focusing specifically on rural banks within the region. The sample was taken from the rural bank branches of five major public banks: Punjab National Bank, Union Bank of India, Bank of Baroda, Canara Bank and Bank of India.

The main purpose of this study is to investigate and evaluate current service quality practices in rural banks, examining everything from the readiness for implementing new service strategies to the benefits or challenges associated with such deployment. A thorough investigation in this area will help identify challenges and failure factors, contributing to the development of guidelines that enhance service encounter policy development, foster prosperous customer relationships, and facilitate long-term market survival.

Table 1: Summary of Research Methodology for the Study

Component	Description
Universe	Customers of Rural Public Sector Banks
Research Design	Descriptive Research
Sampling Method	Probability Sampling
Sampling Unit	Customers of selected Public Sector Banks
Sample Size	302
Sampling Criteria	Market Cap
Geographical area (5)	BKT, Maliha bad, Sarojini Nagar, Chinat, and Goasiganj
Sampling Technique	Stratified Random Sampling
Tools of Analysis Used	Regression, Percentage Analysis

The research design serves as the blueprint for the study, outlining the overarching structure and approach to attain the research objectives. A quantitative research design is adopted, utilizing numerical data collection methods to enable statistical analyses. This design fosters a nuanced assessment of the service quality factors and their impact on customer satisfaction.

3.2 Population, Sample Selection, and Data Collection

The target population consisted of customers from selected public rural sector banks in Lucknow District, Uttar Pradesh, India. Due to practical limitations, a representative sample was drawn using stratified random sampling instead of including the entire population. Data were gathered from primary sources through structured questionnaires based on the SERVQUAL model. The questionnaire included multiple items to assess customers' perceptions of service quality dimensions (Tangibility, Reliability, Responsiveness, Assurance, and Empathy) and their corresponding satisfaction levels. The instrument underwent pre-testing and validation to ensure its reliability and validity.

3.3 Data Analysis and Ethical Considerations

The quantitative data was analyzed using relevant statistical techniques. Descriptive statistics encapsulated demographic details and overall customer satisfaction metrics, while inferential statistics, including regression analysis, helped to explore the relationship between service quality dimensions and customer satisfaction. The significance level was established at $p < 0.05$. The study adhered to ethical principles, preserving the privacy and confidentiality of participants. Informed consent were obtained from all respondents before data collection, and they were granted the option to withdraw from the study at any time.

3.4 Limitations

Potential limitations of the study include the sample size, the geographical constraint (restricted to Lucknow District), and the reliance on self-reported customer perceptions. Despite these limitations, the study aims to provide valuable insights into service quality and customer satisfaction within the context of rural areas in Uttar Pradesh, India.

3.5 Hypothesis Development

The study postulates the following hypotheses to examine the relationships between different dimensions of service quality (Tangibility, Reliability, Assurance, Responsiveness, Empathy) and customer satisfaction. For each dimension D, the hypotheses are formulated as:

- **Null Hypothesis** H_{0D} : There is no significant relationship between the dimension and customer satisfaction.
- **Alternative Hypothesis** H_{1D} : There is a significant relationship between the dimension and customer satisfaction.

1. **Hypothesis 1:** The relationship between Tangibility and customer satisfaction.
2. **Hypothesis 2:** The relationship between Reliability and customer satisfaction.
3. **Hypothesis 3:** The relationship between Assurance and customer satisfaction.
4. **Hypothesis 4:** The relationship between Responsiveness and customer satisfaction.
5. **Hypothesis 5:** The relationship between Empathy and customer satisfaction.

4 Results and Discussion

4.1 Model Summary

Table 2 provides essential statistics to assess the performance and goodness of fit of the regression model utilized in the research.

Table 2: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.975a	.950	.949	.17017

The analysis of the values in Table 2 is presented as follows: The **Model** number denotes the sequence of the model, and in this research, there is only one model. The value of R, representing the multiple correlation coefficient, is 0.975, signifying a strong positive correlation between the predicted and actual values of customer satisfaction, indicating a reliable model. The R value of 0.950 reveals that approximately 95% of the variability in customer satisfaction can be explained by the model's independent variables, reflecting a high explanatory power. The adjusted R value of 0.949, taking into account the number of independent variables and sample size, confirms the model's robustness. Lastly, the standard error of the estimate, 0.17017, quantifies the average deviation between the actual data points and the predicted values, providing insight into the model's accuracy. These statistics collectively demonstrate a well-fitted model that strongly aligns with the observed data, enhancing the confidence in the research findings.

4.2 Statistical Significance of the Model

The statistical significance of the model is demonstrated through an Analysis of Variance (ANOVA), presented in Table 3.

Table 3: ANOVA Table

Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	217.229	5	43.446	1500.395	.000b
Residual	11.438	395	.029		
Total	228.667	400			

Table 3 includes key statistics such as the sum of squares for the regression line (217.229) and the residuals (11.438), representing the variability explained and unexplained by the model, respectively. The mean square values further quantify these variances, with 43.446 for regression and .029 for residual. The model's degrees of freedom are provided with 5 for regression and 395 for the residual, totaling 400. An F value of 1500.395, along with a significance level (Sig.) of .000b, indicates a highly significant model. This reflects that the observed relationships are unlikely to be due to random chance, validating the model and accentuating its ability to accurately represent the underlying relationships in the data. The F ratio thus tests the overall goodness of fit of the data, reinforcing the model's relevance and applicability in the given research context.

4.3 Estimated Model Coefficient

The model's estimated coefficients, which elucidate the relationship between the independent variables and the dependent variable of customer satisfaction, are detailed in Table 4.

Table 4: Estimated Model Coefficient

Model	Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
(Constant)	-1.613	0.106		-15.165	0
Tangibility	0.155	0.031	0.082	5.044	0
Reliability	-0.232	0.027	-0.221	-8.588	0
Responsiveness	0.373	0.028	0.368	13.479	0
Assurance	0.029	0.03	0.029	0.943	0.346
Empathy	1.137	0.035	0.768	32.457	0

Table 4 provides an insightful summary of how the service quality factors influence customer satisfaction in the public rural sector banks in the Lucknow District of Uttar Pradesh. It highlights unstandardized and standardized coefficients, standard errors, t-values, and significance levels for each factor. Notably, the coefficients of Tangibility (0.155), Reliability (-0.232), and Responsiveness (0.373) indicate their positive effects on customer satisfaction, albeit varying in magnitude. The negative coefficient for Reliability suggests a distinct relationship, inviting further investigation. In contrast, Assurance exhibits a non-significant effect, with a coefficient of 0.029 and a higher significance level of 0.346. The standout finding lies in Empathy, demonstrating the strongest positive impact (1.137) on customer satisfaction, as confirmed by its t-value (32.457) and the zero significance level. Together, these findings lend robust empirical support to the model's efficacy in capturing the multifaceted dynamics between service quality attributes and customer satisfaction.

4.4 Hypothesis Testing

The research study investigates the relationship between service quality and customer satisfaction in selected public rural sector banks in the Lucknow District, Uttar Pradesh, India. Based on the provided table and the results of the multiple regression analysis, each hypothesis for the research paper were examined and explained:

Hypothesis 1: The positive beta value of 0.082 for Tangibility (unstandardized coefficient 0.155) indicates a positive relationship with customer satisfaction, significant at $p < 0.001$ (t-value = 5.044). Hence, Hypothesis 1 is supported: as Tangibility increases, so does customer satisfaction.

Hypothesis 2: The negative beta value of -0.221 for Reliability (unstandardized coefficient -0.232) suggests a negative relationship with customer satisfaction, also significant at $p < 0.001$ (t-value = -8.588). Thus, Hypothesis 2 is supported, indicating that decreased reliability leads to reduced customer satisfaction.

Hypothesis 3: Assurance's beta value of 0.029 (unstandardized coefficient 0.029) shows a weak and insignificant relationship with customer satisfaction ($p = 0.346$, t-value = 0.943). Hypothesis 3 is not supported, implying no meaningful impact of Assurance on customer satisfaction.

Hypothesis 4: Responsiveness, with a positive beta value of 0.368 (unstandardized coefficient 0.373), significantly correlates with customer satisfaction at $p < 0.001$ (t-value = 13.479). Hypothesis 4 is supported, showing that enhanced responsiveness leads to increased customer satisfaction.

Hypothesis 5: Empathy has a strong positive beta value of 0.768 (unstandardized coefficient 1.137), and is highly significant at $p < 0.001$ (t-value = 32.457). Hypothesis 5 is supported, revealing that increased empathy results in heightened customer satisfaction.

In summary, the regression analysis confirms that:

- Tangibility and Responsiveness positively influence customer satisfaction.
- Reliability negatively impacts customer satisfaction.
- Assurance lacks a significant effect on customer satisfaction.
- Empathy is strongly and positively related to customer satisfaction.

These findings offer actionable insights for banks to enhance specific service quality factors, such as Reliability and Empathy, and thereby improve overall customer satisfaction levels. Emphasizing aspects directly affecting customer perceptions and experience will contribute to better customer retention and loyalty in the long run.

4.5 Key Findings

The key findings of the study shed light on the relationships between different dimensions of service quality and customer satisfaction in the selected rural public sector banks in Lucknow District, Uttar Pradesh.

Tangibility: The study found a positive relationship between tangibility (physical appearance of facilities, equipment, and personnel) and customer satisfaction. As the tangibility of services increased, customers' satisfaction levels also improved. This implies that investments in improving the physical aspects of bank branches and providing visually appealing services can positively impact customer satisfaction.

Reliability: The research indicated a negative relationship between reliability (consistency and dependability of service provision) and customer satisfaction. When the perception of reliability decreased, customer satisfaction levels also declined. This emphasizes the critical role of reliability in maintaining customer trust and loyalty. Banks should focus on improving processes, reducing errors, and ensuring consistent service delivery.

Assurance: The study did not find a significant relationship between assurance (knowledge and courtesy of employees and their ability to inspire trust and confidence) and customer satisfaction. This suggests that customer satisfaction may not be strongly influenced solely by employee assurance.

Responsiveness: Responsiveness (willingness and promptness in providing service) showed a positive relationship with customer satisfaction. As banks became more responsive to customers' needs and concerns, customer satisfaction levels increased. This highlights the importance of promptly addressing customer queries and resolving issues to enhance overall customer satisfaction.

Empathy: Empathy (caring and individualized attention shown to customers) was found to have a strong positive relationship with customer satisfaction. Banks that demonstrated empathy towards their customers experienced higher levels of customer satisfaction. Empathetic customer service can foster emotional connections with customers, leading to improved customer experiences.

5 Conclusion

This research has provided an insightful examination of service quality and customer satisfaction in the context of rural public sector banks in Lucknow District, Uttar Pradesh. The study successfully unearthed the complex interplay between different dimensions of service quality, such as Tangibility, Reliability, Responsiveness, Assurance, and Empathy, and their significant influence on customer satisfaction. By focusing on rural banking, the research filled an existing gap in the literature, revealing unique challenges and opportunities that are specific to the rural sector. The study's results underscore the critical role that public sector banks play in fostering financial inclusion and rural economic growth. Tailored strategies that meet the unique needs of rural bank customers, as identified in this research, can serve as a valuable guide for bank managers and policymakers. Implementing these strategies may lead to the enhancement of public sector banking services, contributing to sustainable development within rural communities. The ethical considerations and methodological rigor employed throughout the research process further ensure the validity and reliability of the findings. However, limitations such as sample size and geographical constraints must be acknowledged and considered when interpreting the results. Future research could expand the scope by including other regions, analyzing the effect of various technological interventions, or exploring the perspectives of bank employees in addition to customers. Such endeavors would contribute to a more holistic understanding of service quality dynamics in rural banking. In conclusion, this study has elucidated vital aspects of service quality and customer satisfaction in rural public sector banks, offering practical insights and guidelines that could foster better service delivery, customer relationships, and long-term success in the banking sector. The findings serve not only as an academic contribution but also as a strategic roadmap for enhancing rural banking services, ultimately contributing to broader socio-economic growth.

Declaration of Competing Interests

The authors declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

This research did not receive any grants from governmental, private, or nonprofit funding bodies.

Author Contribution

Ved Prakash: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing - original draft, Writing - review and editing **Shubham Pratap Singh**: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - review and editing.

References

[1] L. P. L. Cavaliere, R. Khan, S. Sundram, K. Jainani, G. Bagale, M. K. Chakravarthi, and S. S. Rajest, "The Impact of customer relationship management on customer satisfaction and retention: The mediation of service quality," Turkish Journal of Physiotherapy and Rehabilitation, vol. 32, no. 3, pp. 22107-22121, 2021.

[2] M. A. Hossain, N. Jahan, and M. Kim, "A multidimensional and hierarchical model of banking services and behavioral intentions of customers," International Journal of Emerging Markets, vol. 18, no. 4, pp. 845-867, 2023.

[3] M. Fatima and S. J. Akhtar, "An overview of micro, small and medium enterprises (MSMES) in the state of Uttar Pradesh," EPRA International Journal of Economic and Business Review (JEBR), vol. 11, no. 1, pp. 1-10, 2023.

[4] S. M. Dam and T. C. Dam, "Relationships between service quality, brand image, customer satisfaction, and customer loyalty," The Journal of Asian Finance, Economics and Business, vol. 8, no. 3, pp. 585-593, 2021.

[5] M. U. H. Uzir, H. Al Halbusi, R. Thurasamy, R. L. T. Hock, M. A. Aljaberi, N. Hasan, and M. Hamid, "The effects of service quality, perceived value and trust in home delivery service personnel on customer satisfaction: Evidence from a developing country," Journal of Retailing and Consumer Services, vol. 63, pp. 102721, 2021.

[6] N. Slack, G. Singh, and S. Sharma, "The effect of supermarket service quality dimensions and customer satisfaction on customer loyalty and disloyalty dimensions," International Journal of Quality and Service Sciences, vol. 12, no. 3, pp. 297-318, 2020.

[7] S. Dawadi, S. Shrestha, and R. A. Giri, "Mixed-methods research: A discussion on its types, challenges, and criticisms," Journal of Practical Studies in Education, vol. 2, no. 2, pp. 25-36, 2021.

[8] A. Alshamsi, M. Alshurideh, B. A. Kurdi, and S. A. Salloum, "The influence of service quality on customer retention: A systematic review in the higher education," in Proceedings of the International Conference on Advanced Intelligent Systems and Informatics 2020, pp. 404-416, Springer International Publishing, 2021.

[9] H. Y. Khudhair, D. A. B. Jusoh, A. F. Abbas, A. Mardani, and K. M. Nor, "A review and bibliometric analysis of service quality and customer satisfaction by using Scopus database," International Journal of Management, vol. 11, no. 8, 2020.

[10] D. Grossu-Leibovica and H. Kalkis, "Total quality management tools and techniques for improving service quality and client satisfaction in the healthcare environment: A qualitative systematic review," Management Science Letters, vol. 13, no. 2, pp. 118-123, 2023.

[11] S. A. Shabbir, "Impact of service quality and brand image on brand loyalty: The mediating role of customer satisfaction," Eurasian Journal of Social Sciences, vol. 8, no. 2, pp. 75-84, 2020.

[12] A. Parasuraman, V. A. Zeithaml, and L. L. Berry, "SERVQUAL: a multiple item scale for measuring consumer perception of service quality," Journal of Retailing, vol. 64, no. 1, pp. 12-40, 1998.

[13] D. L. Hawkins and S. Hoon, "The impact of customer retention strategies and the survival of small service-based businesses," 2019.

[14] B. A. Fida, U. Ahmed, Y. Al-Balushi, and D. Singh, "Impact of service quality on customer loyalty and customer satisfaction in Islamic banks in the Sultanate of Oman," Sage Open, vol. 10, no. 2, 2158244020919517, 2020.

[15] A. C. Karunaratna and P. A. P. S. Kumara, "Determinants of Customer Satisfaction in the Mobile Telecommunications Service Industry," Business Insights, vol. 2, no. 2, pp. 03-25, 2022.

[16] M. B. Rahman and N. Chowdhury, "Determinants of customer retention in cellular industry of Bangladesh: a study on young customers," Indonesian Journal of Social Research (IJSR), vol. 4, no. 1, pp. 10-21, 2022.

[17] P. A. Jensen and T. van der Voordt, "Productivity as a value parameter for FM and CREM," Facilities, vol. 39, no. 5/6, pp. 305-320, 2020.

[18] A. Bhadkamkar, K. Garg, D. Pawaskar, M. Kunte, and G. Joshi, "Customer Analytics for E-Business Management," in Changing Face of E-commerce in Asia, pp. 97-119, 2022.

[19] M. Pimić, A. Dukić, and I. Krsmanović, "Empirical research on the impact of hotel service quality on guest loyalty and satisfaction: A case study Serbian hotel industry," Ekonomika, vol. 69, no. 1, pp. 39-57, 2023.

[20] H. Sun, M. R. Rabbani, N. Ahmad, M. S. Sial, G. Cheng, M. Zia-Ud-Din, and Q. Fu, "CSR, co-creation and green consumer loyalty: Are green banking initiatives important? A moderated mediation approach from an emerging economy," Sustainability, vol. 12, no. 24, 10688, 2020.

[21] O. K. Omoregie, J. A. Addae, S. Coffie, G. O. A. Ampong, and K. S. Ofori, "Factors influencing consumer loyalty: evidence from the Ghanaian retail banking industry," International Journal of Bank Marketing, vol. 37, no. 3, pp. 798-820, 2019.

[22] S. B. Egala, D. Boateng, and S. A. Mensah, "To leave or retain? An interplay between quality digital banking services and customer satisfaction," International Journal of Bank Marketing, vol. 39, no. 7, pp. 1420-1445, 2021.

Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in
e-ISSN: 3009-075X

Volume 2 Issue 3

Article Number: 23064

Artificial Intelligence: Revolutionizing Cyber Security in the Digital Era

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Abstract

As we navigate the digital era of the 21st century, cyber security has grown into a pressing societal issue that requires innovative, cutting-edge solutions. In response to this pressing need, Artificial Intelligence (AI) has emerged as a revolutionary instrument, causing a paradigm shift in cyber security. AI's prowess resides in its capacity to process and analyze immense quantities of heterogeneous cyber security data, thereby facilitating the efficient completion of crucial tasks. These duties, which include threat detection, asset prioritization, and vulnerability management, are performed with a level of speed and accuracy that far exceeds human capabilities, thereby transforming our approach to cyber security. This document provides a comprehensive dissection of AI's profound impact on cyber security, as well as an in-depth analysis of how AI tools not only augment, but in many cases transcend human-mediated processes. By delving into the complexities of AI implementation within the realm of cyber security, we demonstrate the potential for AI to effectively anticipate, identify, and preempt cyber threats, empowering organizations to take a proactive stance towards digital safety. Despite these advancements, it is essential to consider the inherent limitations of AI. We emphasize the need for sustained human oversight and intervention to ensure that cyber security measures are proportionate and effective. Importantly, we address potential ethical concerns and emphasize the significance of robust governance structures for the responsible and transparent use of artificial intelligence in cyber security. This paper clarifies the transformative role of AI in reshaping cyber security strategies, thereby contributing to a safer, more secure digital future. In doing so, it sets the groundwork for further exploration and discussion on the use of AI in cyber security, a discussion that is becoming increasingly important as we continue to move deeper into the digital age.

Keywords: Artificial Intelligence; Cyber Security; Vulnerability Management; Control Distribution; Human Senses Mimicry

1 Introduction

The rise of the digital era has revolutionized numerous industries across the globe, including healthcare, finance, and education [1]. Nonetheless, this digital transformation has spawned numerous challenges, especially in cyber security [2–4]. While essential, conventional protection measures such as antivirus software and firewalls are proving insufficient in the face of an ever-changing and increasingly complex cyber threat landscape. The need for dynamic, robust, and effective cyber security solutions has never been greater. The introduction and incorporation of Artificial Intelligence (AI) in cyber security has emerged as a potential game-changer in this context [5–7]. Artificial Intelligence (AI), characterized by its capacity to imitate and potentially surpass human cognitive functions, has been identified as a crucial tool for bolstering cyber security. Using complex algorithms, AI can extract patterns from vast datasets, adapt to new information, and predict with unprecedented accuracy [8, 9]. Its speed, accuracy, and ability to identify novel cyber threats vastly surpass those of conventional security systems, making it an increasingly vital component of cyber security protocols [10–12].

*Corresponding author: kr.sarvi91@gmail.com
Received: 06 July 2023; **Revised:** 25 July 2023; **Accepted:** 29 July 2023; **Published:** 31 August 2023

DOI: 10.57159/gadl.jcmm.2.3.23064.

This introductory section lays the groundwork for the article's exhaustive examination of AI's role in cyber security. Further in this article, the investigation begins by elucidating the current cyber security landscape, emphasizing the diverse nature of current threats and the traditional cyber security measures used to combat them. The section then transitions into an in-depth discussion of how AI techniques, specifically machine learning, deep learning, and natural language processing, are used to enhance cyber security frameworks. In the subsequent sections, we will investigate specific AI applications in cyber security. Real-world examples, such as Symantec's Targeted Attack Analytics (TAA) and Sophos' Intercept X, demonstrate artificial intelligence's tangible impact on enhancing cyber security practices. However, as AI and cyber security become increasingly intertwined, we must be cognizant of the potential pitfalls that AI may introduce. Cyber adversaries may employ AI to execute increasingly sophisticated cyber attacks, posing new cyber security challenges. These escalating challenges necessitate the establishment of stringent ethical frameworks to govern the use of AI in cyber security, as discussed in the following section. The article concludes with a look ahead, predicting how the ongoing development of AI technologies will affect cyber security in the coming years and vice versa. This mini-review aims to provide an overview of AI's potential to enhance cyber security and emphasize the need for circumspect and responsible AI deployment. Through thorough analysis, we hope to cast light on a future in which AI, when used judiciously, can radically alter the cyber security landscape.

2 The Paradigm Shift: Artificial Intelligence in cyber security

AI has emerged as a strategic game-changer in the field of cyber security, radically reshaping traditional threat detection, vulnerability management, and network security processes [13]. This section clarifies AI's transformative role in these domains, highlighting its significant cyber security-revolutionizing strides. Figure 1 represents the possible taxonomy of AI techniques in the cyber security domain.

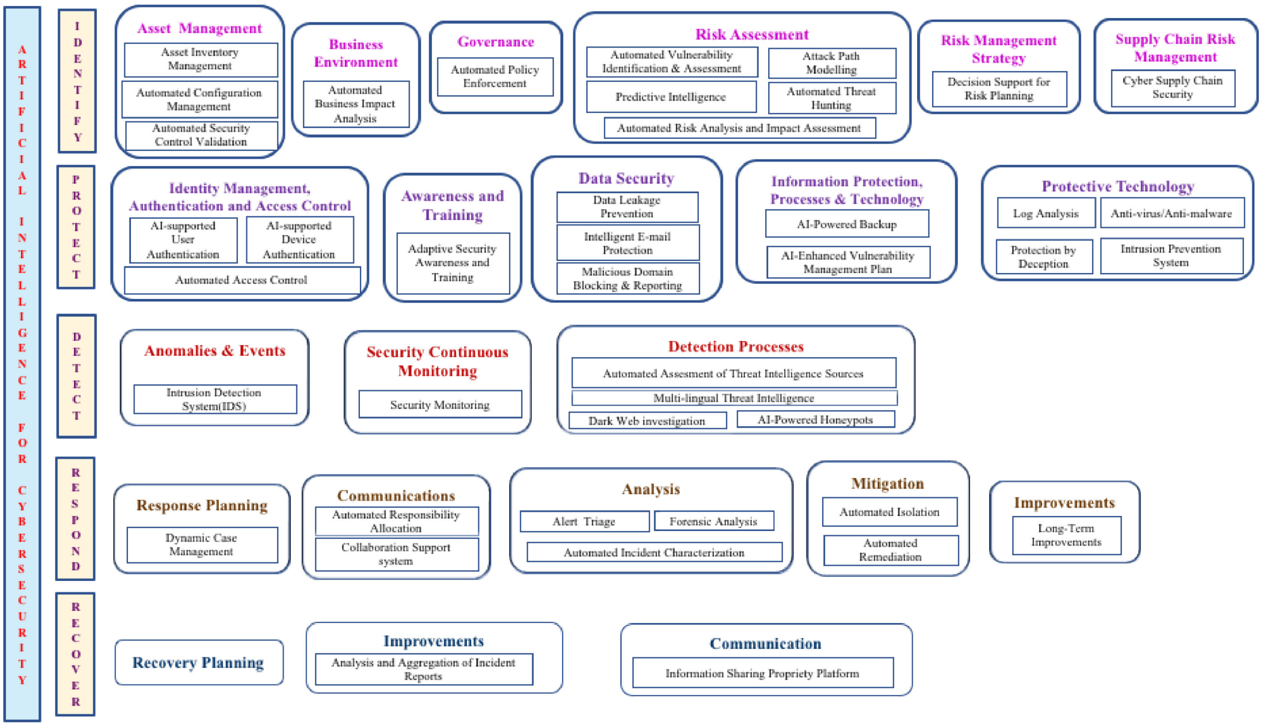

Figure 1: Possible taxonomy of AI techniques in the cyber security domain [14].

2.1 Threat hunting

In the past, cyber security has extensively relied on signature-based techniques for detecting threats. These techniques effectively combat known threats by identifying recurring patterns or 'signatures' associated with particular categories of cyber-attacks [15, 16] this approach has the inherent limitation of being unable to detect and respond promptly to novel, unidentified dangers that do not match known signatures. Herein lies the utility of Artificial Intelligence (AI) power. AI revolutionizes threat hunting by leveraging its powerful predictive capabilities to improve threat detection and identification. AI's strength lies in its capacity to efficiently process and analyze immense quantities of data, recognize meaningful patterns, and eliminate irrelevant noise. This is especially advantageous in the hyper-connected world of today, where the volume of data generated exceeds the computational capacity of conventional threat-hunting techniques [17, 18]. The incorporation of behavioral analysis into AI enables a more dynamic approach to threat detection. Using this method, AI systems can process numerous endpoint data within an organization's network. This information is then used to develop exhaustive application profiles that provide a comprehensive view of normal operational patterns.

These profiles serve as a benchmark for anomaly detection in real-time, where any deviation from the norm may indicate a potential security risk [19–21]. This AI-enhanced strategy results in a significant transition from reactive to proactive cyber security. With AI, organizations can not only identify and respond to threats more quickly, but they also acquire the crucial ability to anticipate and prevent cyberattacks. This transformation results in a cyber security framework that is more robust and better equipped to manage the ever-changing cyber threat landscape [22, 23].

2.2 Vulnerability Management

In the age of digital interconnectivity, managing security vulnerabilities has become exponentially more difficult. Organizations confront an ever-increasing number of potential vulnerabilities and frequently struggle to effectively manage them. Traditional approaches to vulnerability management, which typically follow a reactive paradigm and frequently wait for high-risk vulnerabilities to be exploited before addressing them, have proven insufficient in the current cyber security environment. In this context, the function of Artificial Intelligence (AI) in vulnerability management becomes transformative. The combination of AI and Machine Learning (ML) provides a proactive and predictive approach to vulnerability management [24, 25]. User and Event Behavioral Analytics (UEBA) is a significant approach. UEBA enables AI systems to perpetually analyze and learn from the baseline activity of an organization's user accounts, endpoints, and servers. This analysis aids in the identification of aberrant behaviors that deviate from the established norm. Such deviations or anomalies may indicate the existence of zero-day attacks. Zero-day attacks exploit unknown vulnerabilities before developers are able to create and disseminate patches, making them especially dangerous [26–28]. AI and UEBA can identify these assaults considerably earlier in their lifecycle. AI enables proactive protection against potential breaches, even before vulnerabilities are disclosed and rectified to the public [29, 30]. Thus, AI can inferred to be capable of revolutionizing vulnerability management. It shifts the emphasis from reactive to proactive and predictive measures. This change equips organizations with a comprehensive line of defense against cyber threats, enabling them to secure their digital assets more effectively in a cyber security landscape that is constantly evolving.

2.3 Network Security

Network security remains a critical aspect of any cyber security strategy. Two vital components of network security - creating security policies and understanding network topography - have traditionally been quite labor-intensive and time-consuming tasks [31]. However, Artificial Intelligence (AI) is reshaping this scenario, serving as a potent catalyst for efficiency and effectiveness in these areas. Security policies play an indispensable role in network security, helping identify which network connections are legitimate and which warrant further scrutiny due to potential malicious activity. AI can significantly enhance the formulation of these policies. With AI's ability to analyze vast amounts of data and learn from patterns, it can support the creation of security policies with unprecedented precision and efficiency. This leads to a more robust security framework that proactively identifies and responds to potential threats. Equally important in network security is the understanding of network topography. This involves a deep knowledge of the organization's network, including how various applications and workloads interact with each other. AI's ability to learn from network traffic patterns can significantly simplify this task. AI can suggest a practical grouping of workloads based on their interactions and provide valuable insights to inform security policy development. In essence, AI optimizes these critical aspects of network security and frees up valuable resources. By reducing the time and effort dedicated to policy creation and topography understanding, AI enables security teams to focus more on strategic aspects of network security. This leads to a more robust security posture, better threat identification, and enhanced protection against cyber threats [32–36]. The discussed applications highlight how AI is complementing traditional cyber security strategies and progressively becoming integral to them. In the fight against increasingly sophisticated cyber threats, AI offers a much-needed edge, transforming reactive security practices into proactive defense mechanisms.

3 Navigating the Challenges and Limitations of AI in cyber security

While Artificial Intelligence (AI) stands at the forefront of innovative solutions for cyber security, it is not without its challenges and limitations. The technology's transformative potential is indisputable, but acknowledging its limitations ensures a balanced and realistic approach to its implementation.

3.1 Human adversaries and AI

Artificial Intelligence (AI) has been widely adopted as a powerful tool in cyber security due to its exceptional ability to analyze data, recognize patterns, and predict threats. However, while AI has revolutionized the field, it is essential to acknowledge that it does not render human adversaries obsolete. In fact, sophisticated cybercriminals with specialized strategies can often evade AI systems, proving that the human element in cyber security still poses a significant challenge. Firstly, human adversaries are not static threats. They are creative, intelligent, and capable of adapting their strategies, making them a persistent risk despite advanced AI defenses. They can use techniques like 'data poisoning' or 'adversarial attacks' to manipulate the learning process of AI systems.

By injecting misleading or incorrect data, they can skew the AI model's understanding and decision-making, causing it to misidentify threats or overlook vulnerabilities [37–40]. Moreover, human adversaries can also take advantage of the inherent limitations of AI systems. For instance, AI models are predominantly based on historical data. Thus, they may struggle to accurately predict or respond to completely novel attack strategies that have not been previously encountered. This is where the intuition and experience of human cyber security experts are irreplaceable [41–44]. Therefore, while AI is a potent tool for automating and enhancing many aspects of cyber security, human vigilance, expertise, and adaptability should not be undervalued. Effective cyber security requires a symbiotic relationship between AI capabilities and human oversight. After all, in the intricate and evolving landscape of cyber security threats, the human element continues to be crucial in identifying, understanding, and mitigating potential risks.

3.2 AI-powered cyber attacks

AI's growing power and sophistication is not only a boon for cyber security efforts but, paradoxically, a potential catalyst for more potent and sophisticated cyber threats. As we explore the cyber security advantages of AI, we must also be wary of its weaponization potential, particularly its capacity to fuel AI-powered cyberattacks. In the hands of a malevolent actor, AI can serve as a potent tool for automating and scaling cyber threats. With AI, cybercriminals can quickly adapt to defensive measures, execute attacks at unprecedented speeds, and exploit vulnerabilities with greater precision. AI can even enable attackers to mimic human behavior, making phishing attacks more convincing and more likely to succeed [45, 44, 46–48]. Moreover, AI can assist in crafting 'smart' malware, capable of learning from the environment it infiltrates, adjusting its strategies to avoid detection, and maximizing the damage it inflicts. This means traditional security defenses, such as signature-based malware detection, are often inadequate against these advanced threats. One such example of this emerging threat is DeepLocker, a new breed of highly targeted and evasive attack tool powered by AI and unleashed by IBM Research. DeepLocker conceals its malicious intent until it reaches a specific victim, demonstrating the potential future sophistication of malware threats [46, 47]. In essence, while AI undoubtedly enhances our defensive capabilities in the cyber security realm, it also provides adversaries with the tools to craft more sophisticated, adaptable, and damaging attacks. The emerging reality of AI-powered cyber threats underscores the need to continually evolve and improve our AI-based defenses and maintain robust human oversight.

3.3 Ethical considerations and governance

The integration of AI into the fabric of cyber security entails navigating a complex web of ethical issues and implications. Though central to its utility in threat detection and prevention, the vast analytical capabilities of AI also surface significant concerns regarding data privacy and protection. As AI systems are trained on and analyze enormous volumes of data, striking a balance between leveraging this data for cyber security and safeguarding user privacy is critical. Adding to the complexity is the 'black box' problem - the lack of transparency and interpretability in the decision-making processes of some AI models [49, 50]. As AI becomes increasingly integral to cyber security, this opacity can obfuscate accountability and complicate rectifying security breaches or failures. Moreover, the susceptibility of AI to malicious use, including the creation of AI-powered cyber threats, emphasizes the urgency of ethical considerations. Unchecked, these threats could exploit AI's power to inflict wide-ranging damage, calling for stringent ethical and regulatory controls over the use of AI in this domain. In light of these challenges, robust governance structures and regulatory frameworks are necessary to steer the ethical deployment of AI in cyber security. Such measures should enforce transparency, uphold data privacy, ensure accountability, and set out clear guidelines to mitigate the potential misuse of AI [49–51]. In this way, we can responsibly harness the potential of AI to enhance cyber security while safeguarding against its risks. Therefore, the incorporation of AI in cyber security is not a panacea but a powerful tool that brings its own complexities. Navigating these challenges necessitates a measured approach that blends AI's strengths with human oversight, ethical practices, and resilient governance.

4 Case Studies Illustrating the Role of AI in cyber security

Artificial Intelligence's potential in bolstering cyber security has been increasingly recognized and harnessed by organizations worldwide. This is evident in various real-world implementations, where AI-driven tools and solutions have been used to fortify defenses, enhance threat detection, and manage vulnerabilities. Here, we explore a few notable case studies that illuminate AI's transformative role in the realm of cyber security:

4.1 Symantec's targeted attack analytics (TAA) tool

Symantec's Targeted Attack Analytics (TAA) tool is a leading example of how artificial intelligence (AI) is being applied in the field of cyber security. This innovative tool leverages the power of AI to automatically analyze vast amounts of data and identify indicators of a security breach. TAA uses advanced AI algorithms that mimic the processes, data analysis, and functions of experienced security experts. By 'learning' from human professionals, TAA can detect targeted attacks with high accuracy [52, 53]. Figure 2 represents the working principle of the discussed TAA tool.

In 2018, TAA demonstrated its effectiveness in identifying and responding to sophisticated threats when it was crucial in combating a Dragonfly 2.0 attack. This incident showcased the tool's ability to proactively detect threats and manage incidents, significantly improving the efficiency of cyber security responses. Integrating AI in tools like TAA represents a major advancement in proactive threat detection and incident management [50]. By harnessing the power of AI, cyber security professionals are able to more effectively protect against and respond to targeted attacks, substantially boosting the overall security of their systems.

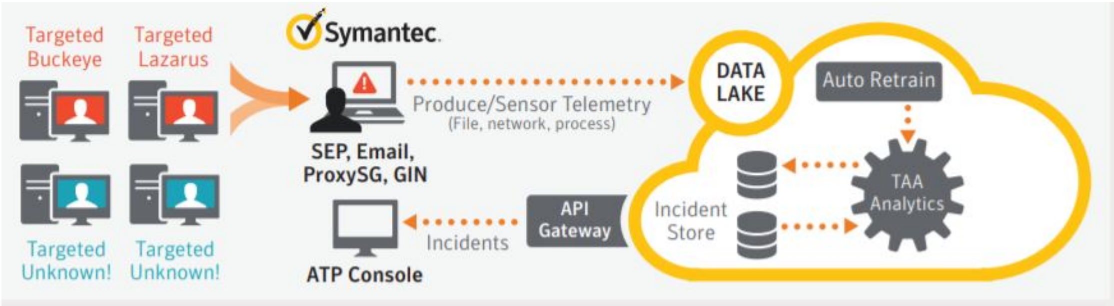

Figure 2: Working principle of the Symantec's TAA tool [54]

4.2 Sophos' intercept X

Sophos' Intercept X tool is a powerful application of artificial intelligence (AI) in the field of cyber security. This advanced tool uses deep learning neural networks, modeled after how the human brain functions, to distinguish between benign and malicious files accurately. Intercept X can analyze thousands of features from a file, conduct in-depth analysis, and determine whether the file is safe or potentially harmful within milliseconds [55–57]. Figure 3 presents the summary of the discussed Sophos' tool.

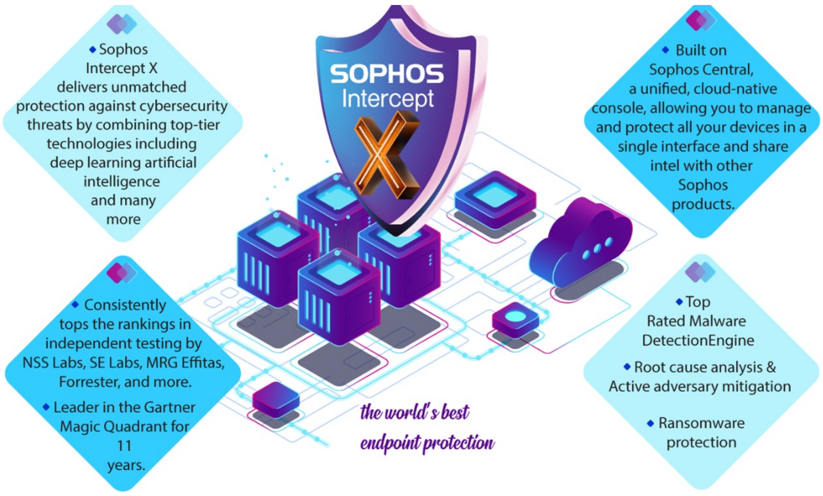

Figure 3: Summary of Sophos' intercept X tool [58].

The system is trained on real-world feedback and two-way threat intelligence, resulting in high accuracy for detecting both existing malware and zero-day threats. Additionally, Intercept X maintains a low false-positive rate, minimizing the risk of incorrectly identifying benign files as malicious. This case study reflects the potential of AI in fortifying defense mechanisms against cyber threats. By leveraging the power of AI, tools like Intercept X can bring agility and accuracy to malware detection and threat prevention, significantly improving the overall security of systems [59–61].

4.3 IBM's QRadar advisor with Watson

IBM has made significant advancements in integrating AI in cyber security with its QRadar Advisor tool. This tool uses the cognitive computing capabilities of IBM Watson to investigate potential security incidents automatically. By employing AI, the QRadar Advisor can assist security analysts in assessing threat incidents and reduce the risk of overlooking significant threats. In this case, The application of AI improves efficiency and enhances the accuracy of threat detection and response. Using advanced AI algorithms, the QRadar Advisor can quickly analyze large amounts of data and identify potential threats with high accuracy. This ultimately strengthens an organization's cyber security infrastructure by providing security analysts with powerful tools to detect and respond to cyber threats [62, 63, 15]. Figure 4 represents the three stages involved in the working of the discussed IBM tool.

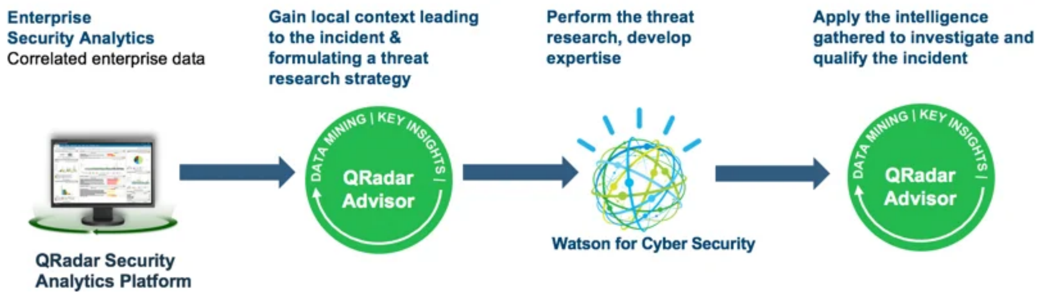

Figure 4: Stages involved in the working of IBM's QRadar advisor with Watson [64].

4.4 DeepLocker

While AI has been used to improve cyber security, it has also been used maliciously, as seen in the creation of DeepLocker - a new form of AI-powered malware. Unlike traditional malware, DeepLocker can conceal its malicious intent until it reaches a specific victim, making it incredibly difficult to detect and counter. This advanced malware uses AI and indicators such as facial recognition and geolocation to identify its target accurately. This case highlights the double-edged nature of AI in cyber security. While AI can be used to improve defenses against cyber threats, it can also be used to create advanced malware that is difficult to detect and counter. This underscores the importance of continuous advancement in AI-powered cyber security tools and measures to avoid malicious uses of AI [65–67]. Figure 5 depicts the overview of the discussed Deeplocker malware.

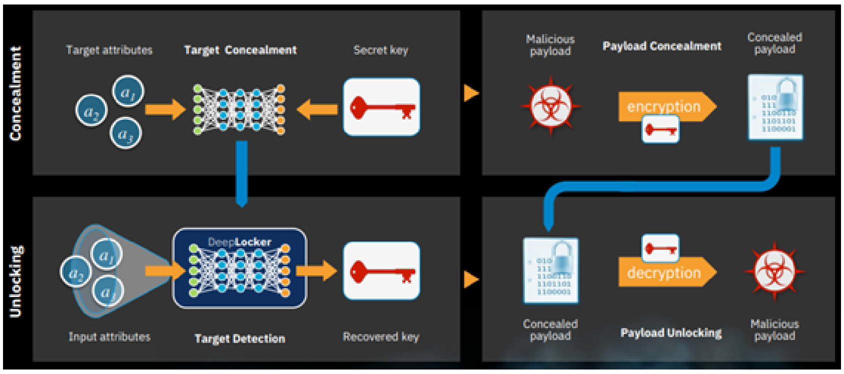

Figure 5: Process flow of deeplocker AI malware [68]

These case studies demonstrate that AI, when applied effectively, can greatly enhance cyber security. However, as seen in the DeepLocker instance, it also emphasizes the necessity of keeping pace with the evolving threat landscape where AI itself could be weaponized. From automating the detection of complex threats to learning from real-time data for proactive defense, AI is becoming a cornerstone in shaping robust and resilient cyber security strategies.

5 Future Trends and Predictions in AI and cyber security

The trajectory of Artificial Intelligence (AI) in cyber security is steeply upward, propelled by advancements in technology, rising digital threats, and the pressing need for more robust, adaptive defenses. The fusion of AI and cyber security is set to reshape the cyber landscape, bringing forth transformative changes in how organizations protect their digital assets. Here we delve into future trends and predictions in this dynamic domain:

5.1 Growth in AI-Powered cyber security market

The market for AI in cyber security is expected to experience exponential growth in the near future. Recent reports have projected that the market will expand from its current value of USD 8.8 billion in 2019 to an impressive USD 38.2 billion by 2026. This growth can be attributed to several factors, including the increasing digitization of businesses and the proliferation of connected devices. As more and more businesses move their operations online, the risk of cyber attacks increases, leading to growing concerns over data privacy and security. This has fueled demand for AI-powered cyber security solutions that can help businesses protect their data and operations. In addition to these factors, significant growth opportunities are presented by the increasing demand for AI-powered solutions among Small and Medium Enterprises (SMEs). As these businesses grow and expand their online presence, they are becoming more vulnerable to cyber attacks and therefore seeking advanced cyber security solutions to protect themselves.

Additionally, the increased use of social media for business purposes has also created new vulnerabilities that AI-powered cyber security solutions can address [69–71]. Figure 6 summarizes the anticipated global growth in AI-powered cyber security market.

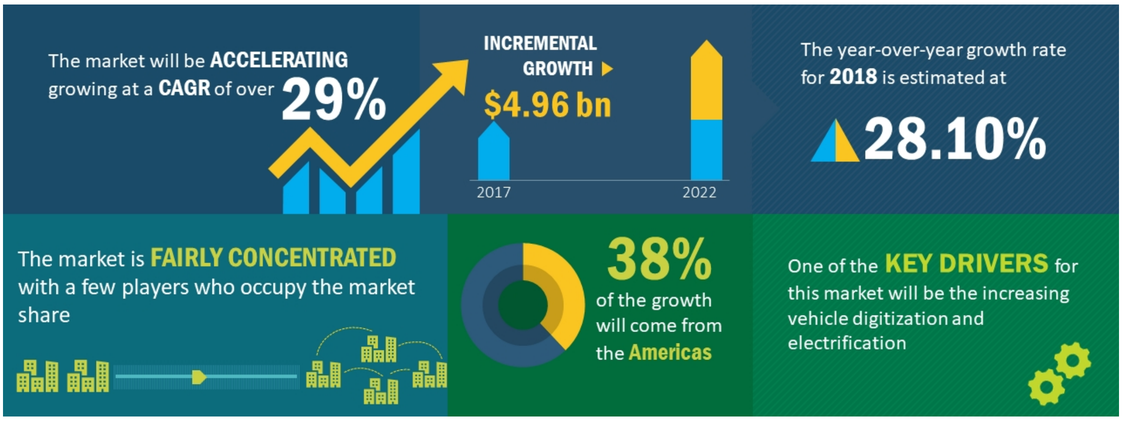

Figure 6: Anticipated global growth of AI-powered cyber security market [72].

5.2 Emergence of AI-enabled threats

As AI technology advances and becomes more sophisticated, there is a growing potential for its misuse in the form of AI-powered cyber threats. These threats can take many forms, including intelligent malware that can learn and adapt to evade detection by traditional security measures or automated phishing attacks that can accurately mimic human writing styles to trick users into revealing sensitive information. One example of this trend is the DeepLocker case, in which researchers demonstrated the potential for AI to be used to create highly targeted and evasive malware. This case highlights the critical need for advanced AI-driven defenses that can keep pace with the rapidly evolving threat landscape. As AI technology continues to advance, it is likely that we will see a surge in these types of AI-powered cyber threats. This underscores the importance of continued investment in advanced cyber security solutions to effectively defend against these emerging threats [65–67, 73, 74]. Figure 7 summarizes the various possible threats that might be posed by the emerging AI.

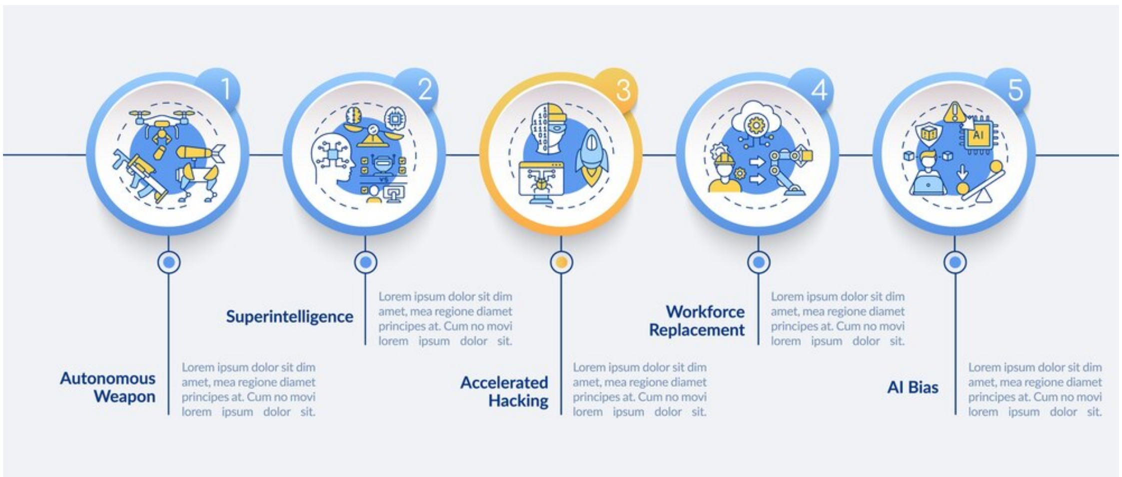

Figure 7: Possible threats concerned with the emergence of AI [75].

5.3 Integration of AI and other emerging technologies

In the coming years, we will likely see a deeper integration of AI with other emerging technologies, such as blockchain and the Internet of Things (IoT), to enhance cyber security. These technologies have the potential to work together in powerful ways to create more secure systems and networks. For example, AI and blockchain could be combined to create decentralized systems that are more resistant to cyber attacks. Blockchain technology allows for creating secure, tamper-proof records that can be distributed across a network, making it difficult for attackers to compromise the system. Integrating AI into these systems makes it possible to create intelligent, self-healing networks that can automatically detect and respond to threats [75, 73, 76]. Similarly, AI can also help monitor and secure the vast networks of devices that make up the IoT. With billions of connected devices worldwide, it is becoming increasingly difficult to ensure that these devices are secure and not being used as entry points for cyber attacks. By integrating AI into these networks, it would be possible to automatically monitor device behavior and detect any anomalies indicating a potential security threat [77–82].

5.4 AI-powered automation in cyber security

AI technology is playing an increasingly important role in driving automation in the field of cyber security. By automating many of the routine and mundane tasks associated with cyber security, AI enables security personnel to focus on more strategic aspects of their work, such as threat analysis and incident response. One area where AI has a significant impact is in the automation of threat detection. Using advanced machine learning algorithms, AI-powered tools can automatically analyze vast amounts of data to identify potential security threats. This can help security teams to detect and respond to emerging threats quickly, reducing the risk of a successful cyber attack. In addition to threat detection, AI is also being used to automate other aspects of cyber security, such as incident response and vulnerability management. For example, AI-powered tools can automatically analyze security incidents to determine the most appropriate response or automatically scan systems for vulnerabilities and suggest remediation actions [44, 79, 83].

5.5 Greater emphasis on AI governance in cyber security

As AI technology continues to play a growing role in the field of cyber security, there is an increasing need for ethical and transparent AI practices. This will require organizations to establish robust AI governance frameworks to ensure that AI is being used ethically and responsibly, and to mitigate any potential risks associated with its use. AI governance refers to the policies, processes, and practices put in place to ensure that AI is being used in a way consistent with an organization's values and ethical principles. This can include measures such as transparency and explainability, which help ensure that AI systems are making decisions in a way that human users can understand and scrutinize. In the context of cyber security, AI governance is particularly important because of the potential risks associated with the misuse of AI technology. For example, if an AI system is not properly governed, it could be used to carry out cyber attacks or other malicious activities. To mitigate these risks, organizations must establish robust AI governance frameworks that include regular audits and risk assessments [84–86]. From the disucussion so far, it can be infered that the future of AI in cyber security is laden with both enormous potential and significant challenges. As we embrace this promising future, the focus must be on harnessing AI's power responsibly and ethically, building robust defenses, and staying vigilant of the evolving threat landscape. The constant interplay between advancing AI capabilities and emerging threats necessitates a future-proof cyber security strategy – one that continuously evolves, learns, and adapts.

6 Conclusion

The advent of Artificial Intelligence (AI) has ushered in a new era of cyber security, opening up unprecedented avenues for combating the escalating threat landscape. AI's capability to learn, adapt, and counteract cyber threats has demonstrated its substantial potential as an indispensable asset within cyber security arsenals. However, it is essential to recognize that this is only the dawn of AI's journey within the realm of cyber security. There are vast uncharted territories yet to be explored, understood, and mastered. The relentless evolution of cyber threats necessitates an equally dynamic response, which AI is well-positioned to provide. Yet, the utilization of AI in isolation may not fully address the complexity and diversity of the cyber threats we face today. The future of effective cyber security lies in a symbiotic integration of AI's speed and scalability with human expertise's creativity, intuition, and ethical judgment. This fusion of human and machine intelligence will provide a more holistic approach to identifying, responding to, and preempting cyber threats. Furthermore, as we leverage AI's transformative potential, it is paramount to maintain a focus on the ethical implications of its use. The governance of AI in cyber security must be marked by transparency, accountability, and inclusivity, thereby ensuring its responsible application. In conclusion, the revolution of AI in cyber security is underway. With continued research, responsible governance, and ethical use, AI's transformative potential can be harnessed to its fullest extent, ultimately guiding us towards a safer and more secure digital future. While challenges lie ahead, the potential benefits of AI in cyber security are immense, promising a proactive and adaptable approach to secure our increasingly interconnected world.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

This research did not receive any grants from governmental, private, or nonprofit funding bodies.

Author Contribution

Sarvesh Kumar: Conceptualization, Methodology, Supervision, Writing - review and editing. **Upasana Gupta**: Investigation, Visualization, Writing - original draft. **Arvind Kumar Singh**: Investigation, Visualization, Writing - original draft. **Avadh Kishore Singh**: Resources, Investigation, Visualization, Writing - original draft.

References

[1] A. Kish, "Machine Learning: A Review of Methods and Applications," *Researchgate.Net*, 2018.

[2] P. Liu and C. Lu, "Strategic analysis and development plan design on digital transformation in the energy industry: A global perspective," *International Journal of Energy Research*, vol. 45, pp. 19657–19670, nov 2021.

[3] J. B. Schmitt, A. Goldmann, S. T. Simon, and C. Bieber, "Conception and Interpretation of Interdisciplinarity in Research Practice: Findings from Group Discussions in the Emerging Field of Digital Transformation," *Minerva*, vol. 61, pp. 199–220, jun 2023.

[4] A. Modi, B. Kishore, D. K. Shetty, V. P. Sharma, S. Ibrahim, R. Hunain, N. Usman, S. G. Nayak, S. Kumar, and R. Paul, "Role of Artificial Intelligence in Detecting Colonic Polyps during Intestinal Endoscopy," *Engineered Science*, vol. 20, pp. 23–30, 2022.

[5] D. A. B. Fernandes, L. F. B. Soares, J. V. Gomes, M. M. Freire, and P. R. M. Inácio, "Security issues in cloud environments: a survey," *International Journal of Information Security*, vol. 13, pp. 113–170, apr 2014.

[6] V. Mullet, P. Sondi, and E. Ramat, "A Review of Cybersecurity Guidelines for Manufacturing Factories in Industry 4.0," *IEEE Access*, vol. 9, pp. 23235–23263, 2021.

[7] B. Shin and P. B. Lowry, "A review and theoretical explanation of the 'Cyberthreat-Intelligence (CTI) capability' that needs to be fostered in information security practitioners and how this can be accomplished," *Computers & Security*, vol. 92, p. 101761, may 2020.

[8] M. Naveed Uddin, "Cognitive science and artificial intelligence: simulating the human mind and its complexity," *Cognitive Computation and Systems*, vol. 1, pp. 113–116, dec 2019.

[9] P. Mikalef and M. Gupta, "Artificial intelligence capability: Conceptualization, measurement calibration, and empirical study on its impact on organizational creativity and firm performance," *Information & Management*, vol. 58, p. 103434, apr 2021.

[10] A. Kumar, M. Rahmath, Y. Raju, S. Reddy Vulapula, B. R. Prathap, M. M. Hassan, M. A. Mohamed, and S. A. Asakipaam, "Enhanced Secure Technique for Detecting Cyber Attacks Using Artificial Intelligence and Optimal IoT," *Security and Communication Networks*, vol. 2022, pp. 1–13, jul 2022.

[11] R. Trifonov, O. Nakov, and V. Mladenov, "Artificial Intelligence in Cyber Threats Intelligence," in *2018 International Conference on Intelligent and Innovative Computing Applications (ICONIC)*, pp. 1–4, IEEE, dec 2018.

[12] A. Amarasinghe, W. Wijesinghe, D. Nirmana, A. Jayakody, and A. Priyankara, "AI Based Cyber Threats and Vulnerability Detection, Prevention and Prediction System," in *2019 International Conference on Advancements in Computing (ICAC)*, pp. 363–368, IEEE, dec 2019.

[13] R. Gruetzemacher and J. Whittlestone, "The transformative potential of artificial intelligence," *Futures*, vol. 135, p. 102884, jan 2022.

[14] R. Kaur, D. Gabrijelčič, and T. Klobučar, "Artificial intelligence for cybersecurity: Literature review and future research directions," *Information Fusion*, vol. 97, p. 101804, sep 2023.

[15] M. M. Yamin, M. Ullah, H. Ullah, and B. Katt, "Weaponized AI for cyber attacks," *Journal of Information Security and Applications*, vol. 57, 2021.

[16] S. C. Pallaprolu, J. M. Namayanja, V. P. Janeja, and C. T. S. Adithya, "Label propagation in big data to detect remote access Trojans," in *2016 IEEE International Conference on Big Data (Big Data)*, pp. 3539–3547, IEEE, dec 2016.

[17] A. Syrowatka, M. Kuznetsova, A. Alsubai, A. L. Beckman, P. A. Bain, K. J. T. Craig, J. Hu, G. P. Jackson, K. Rhee, and D. W. Bates, "Leveraging artificial intelligence for pandemic preparedness and response: a scoping review to identify key use cases," *npj Digital Medicine*, vol. 4, p. 96, jun 2021.

[18] M. Ebrahimi, J. F. Nunamaker, and H. Chen, "Semi-Supervised Cyber Threat Identification in Dark Net Markets: A Transductive and Deep Learning Approach," *Journal of Management Information Systems*, vol. 37, pp. 694–722, jul 2020.

[19] Y. Xu, X. Liu, X. Cao, C. Huang, E. Liu, S. Qian, X. Liu, Y. Wu, F. Dong, C.-W. Qiu, J. Qiu, K. Hua, W. Su, J. Wu, H. Xu, Y. Han, C. Fu, Z. Yin, M. Liu, R. Roepman, S. Dietmann, M. Virta, F. Kengara, Z. Zhang, L. Zhang, T. Zhao, J. Dai, J. Yang, L. Lan, M. Luo, Z. Liu, T. An, B. Zhang, X. He, S. Cong, X. Liu, W. Zhang, J. P. Lewis, J. M. Tiedje, Q. Wang, Z. An, F. Wang, L. Zhang, T. Huang, C. Lu, Z. Cai, F. Wang, and J. Zhang, "Artificial intelligence: A powerful paradigm for scientific research," *The Innovation*, vol. 2, p. 100179, nov 2021.

[20] T. Kabudi, I. Pappas, and D. H. Olsen, "AI-enabled adaptive learning systems: A systematic mapping of the literature," *Computers and Education: Artificial Intelligence*, vol. 2, p. 100017, 2021.

[21] N. Haefner, J. Wincent, V. Parida, and O. Gassmann, "Artificial intelligence and innovation management: A review, framework, and research agenda," *Technological Forecasting and Social Change*, vol. 162, p. 120392, jan 2021.

[22] G. Banga, "Using Artificial Intelligence in Cybersecurity," *Www.Balbix.Com*, 2020.

[23] Y. Li and Q. Liu, "A comprehensive review study of cyber-attacks and cyber security; Emerging trends and recent developments," *Energy Reports*, vol. 7, pp. 8176–8186, nov 2021.

[24] D. Perwej, S. Qamar Abbas, J. Pratap Dixit, D. N. Akhtar, and A. Kumar Jaiswal, "A Systematic Literature Review on the Cyber Security," *International Journal of Scientific Research and Management*, vol. 9, pp. 669–710, dec 2021.

[25] B. Li, Y. Feng, Z. Xiong, W. Yang, and G. Liu, "Research on AI security enhanced encryption algorithm of autonomous IoT systems," *Information Sciences*, vol. 575, pp. 379–398, oct 2021.

[26] S. R. Potula, R. Selvanambi, M. Karuppiah, and D. Pelusi, "Artificial Intelligence-Based Cyber Security Applications," pp. 343–373, 2023.

[27] M. Graham, R. Kukla, O. Mandrychenko, D. Hart, and J. Kennedy, "Developing Visualisations to Enhance an Insider Threat Product: A Case Study," in *2021 IEEE Symposium on Visualization for Cyber Security (VizSec)*, pp. 47–57, IEEE, oct 2021.

[28] R. Dolas, "Analytic-driven decision support in cybersecurity : towards effective IP risk management decision-making process.," tech. rep., UNIVERSITY OF TWENTE, 2023.

[29] D. Schlette, "Cyber Threat Intelligence," in *Encyclopedia of Cryptography, Security and Privacy*, pp. 1–3, Berlin, Heidelberg: Springer Berlin Heidelberg, 2021.

[30] M. Ahmed, N. Moustafa, A. Barkat, and P. Haskell-Dowland, *Next-Generation Enterprise Security and Governance*. Boca Raton: CRC Press, feb 2022.

[31] M. Kaeo, "Designing Network Security," p. 745, 2003.

[32] J. Cheng, Y. Yang, X. Tang, N. Xiong, Y. Zhang, and F. Lei, "Generative adversarial networks: A literature review," *KSII Transactions on Internet and Information Systems*, vol. 14, no. 12, pp. 4625–4647, 2020.

[33] Y. Hu, W. Kuang, Z. Qin, K. Li, J. Zhang, Y. Gao, W. Li, and K. Li, "Artificial Intelligence Security: Threats and Countermeasures," *ACM Computing Surveys*, vol. 55, no. 1, 2021.

[34] I. H. Sarker, M. H. Furhad, and R. Nowrozy, "AI-Driven Cybersecurity: An Overview, Security Intelligence Modeling and Research Directions," *SN Computer Science*, vol. 2, no. 3, 2021.

[35] M. Amrollahi, S. Hadayeghparast, H. Karimipour, F. Derakhshan, and G. Srivastava, "Enhancing network security via machine learning: Opportunities and challenges," *Handbook of Big Data Privacy*, pp. 165–189, 2020.

[36] F. Fourati and M.-S. Alouini, "Artificial intelligence for satellite communication: A review," *Intelligent and Converged Networks*, vol. 2, no. 3, pp. 213–243, 2021.

[37] O. Eigner, S. Eresheim, P. Kieseberg, L. D. Klausner, M. Pirker, T. Priebe, S. Tjoa, F. Marulli, and F. Mercaldo, "Towards resilient artificial intelligence: Survey and research issues," *Proceedings of the 2021 IEEE International Conference on Cyber Security and Resilience, CSR 2021*, pp. 536–542, 2021.

[38] S. Zhou, C. Liu, D. Ye, T. Zhu, W. Zhou, and P. S. Yu, "Adversarial Attacks and Defenses in Deep Learning: From a Perspective of Cybersecurity," *ACM Computing Surveys*, vol. 55, no. 8, pp. 1–39, 2023.

[39] A. Chakraborty, M. Alam, V. Dey, A. Chattopadhyay, and D. Mukhopadhyay, "A survey on adversarial attacks and defences," *CAAI Transactions on Intelligence Technology*, vol. 6, no. 1, pp. 25–45, 2021.

[40] F. Aloraini, A. Javed, O. Rana, and P. Burnap, "Adversarial machine learning in IoT from an insider point of view," *Journal of Information Security and Applications*, vol. 70, 2022.

[41] R. S. Sangwan, Y. Badr, and S. M. Srinivasan, "Cybersecurity for AI Systems: A Survey," *Journal of Cybersecurity and Privacy*, vol. 3, pp. 166–190, may 2023.

[42] A. Ayodeji, M. Mohamed, L. Li, A. Di Buono, I. Pierce, and H. Ahmed, “Cyber security in the nuclear industry: A closer look at digital control systems, networks and human factors,” *Progress in Nuclear Energy*, vol. 161, 2023.

[43] S. Kaviani, K. J. Han, and I. Sohn, “Adversarial attacks and defenses on AI in medical imaging informatics: A survey,” *Expert Systems with Applications*, vol. 198, 2022.

[44] N. Kaloudi and L. I. Jingyue, “The AI-based cyber threat landscape: A survey,” *ACM Computing Surveys*, vol. 53, no. 1, 2020.

[45] B. Guembe, A. Azeta, S. Misra, V. C. Osamor, L. Fernandez-Sanz, and V. Pospelova, “The Emerging Threat of Ai-driven Cyber Attacks: A Review,” *Applied Artificial Intelligence*, vol. 36, dec 2022.

[46] T. C. Truong, Q. B. Diep, and I. Zelinka, “Artificial Intelligence in the Cyber Domain: Offense and Defense,” *Symmetry*, vol. 12, p. 410, mar 2020.

[47] L. Fritsch, A. Jaber, and A. Yazidi, “An Overview of Artificial Intelligence Used in Malware,” in *Communications in Computer and Information Science*, vol. 1650 CCIS, pp. 41–51, 2022.

[48] L. Fritsch, A. Jaber, and A. Yazidi, “An Overview of Artificial Intelligence Used in Malware,” *Communications in Computer and Information Science*, vol. 1650 CCIS, pp. 41–51, 2022.

[49] J. Chen, C. Su, and Z. Yan, “AI-Driven Cyber Security Analytics and Privacy Protection,” *Security and Communication Networks*, vol. 2019, 2019.

[50] B. Murdoch, “Privacy and artificial intelligence: challenges for protecting health information in a new era,” *BMC Medical Ethics*, vol. 22, no. 1, 2021.

[51] R. Blackman, “A Practical Guide to Building Ethical AI,” tech. rep., 2020.

[52] V. Liagkou, C. Stylios, L. Pappa, and A. Petunin, “Challenges and opportunities in industry 4.0 for mechatronics, artificial intelligence and cybernetics,” *Electronics (Switzerland)*, vol. 10, no. 16, 2021.

[53] Thiyagarajan P., “A Review on Cyber Security Mechanisms Using Machine and Deep Learning Algorithms,” pp. 23–41, 2019.

[54] CyberMaterial, “Symantec’s Targeted Attack analytics Tool (TAA).”

[55] T. M. Ghazal, M. K. Hasan, R. A. Zitar, N. A. Al-Dmour, W. T. Al-Sit, and S. Islam, “Cybers Security Analysis and Measurement Tools Using Machine Learning Approach,” *2022 1st International Conference on AI in Cybersecurity, ICAIC 2022*, 2022.

[56] N. Kshetri, “Economics of Artificial Intelligence in Cybersecurity,” *IT Professional*, vol. 23, no. 5, pp. 73–77, 2021.

[57] I. Abusamrah, A. Madhoun, and S. Iseed, “Next-Generation Firewall, Deep Learning Endpoint Protection and Intelligent SIEM Integration,” 2021.

[58] Sight and Sound Computers Limited, “Sophos Intercept X,” 2020.

[59] K. Hamid, M. W. Iqbal, M. Aqeel, X. Liu, and M. Arif, “Analysis of Techniques for Detection and Removal of Zero-Day Attacks (ZDA),” pp. 248–262, 2023.

[60] C. A. Teodorescu, “Perspectives and Reviews in the Development and Evolution of the Zero-Day Attacks,” *Informatica Economica*, vol. 26, no. 2/2022, pp. 46–56, 2022.

[61] A. Kapoor, A. Gupta, R. Gupta, S. Tanwar, G. Sharma, and I. E. Davidson, “Ransomware detection, avoidance, and mitigation scheme: A review and future directions,” *Sustainability (Switzerland)*, vol. 14, no. 1, 2022.

[62] R. Das and R. Sandhane, “Artificial Intelligence in Cyber Security,” *Journal of Physics: Conference Series*, vol. 1964, no. 4, 2021.

[63] D. Sasikala and K. Venkatesh Sharma, “Deployment of Artificial Intelligence with Bootstrapped Meta-Learning in Cyber Security,” *Journal of Trends in Computer Science and Smart Technology*, vol. 4, no. 3, pp. 139–152, 2022.

[64] V. Dheap, “IBM QRadar Advisor with Watson: Revolutionizing the Way Security Analysts Work,” tech. rep., 2017.

[65] G. Schram, “The Role of Artificial Intelligence in Cyber Operations: An Analysis of AI and Its Application to Malware-Based Cyberattacks and Proactive Cybersecurity,” *ProQuest Dissertations and Theses*, p. 49, 2021.

[66] M. Taddeo, “Three Ethical Challenges of Applications of Artificial Intelligence in Cybersecurity,” *Minds and Machines*, vol. 29, no. 2, pp. 187–191, 2019.

[67] N. Yu, Z. Tuttle, C. J. Thurnau, and E. Mireku, “AI-powered GUI attack and its defensive methods,” *ACMSE 2020 - Proceedings of the 2020 ACM Southeast Conference*, pp. 79–86, 2020.

[68] T. Terada, T. Sakamoto, Y. Kokubu, A. Yamatani, I. Takaesu, R. Inoue, T. Ozawa, and T. Isayama, “DeepLocker : AI-embedded attack,” tech. rep., 2020.

[69] M. F. Ansari, B. Dash, P. Sharma, and N. Yathiraju, “The Impact and Limitations of Artificial Intelligence in Cybersecurity: A Literature Review,” *Ijarcce*, vol. 11, no. 9, 2022.

[70] K. AL-Dosari, N. Fetais, and M. Kucukvar, “Artificial Intelligence and Cyber Defense System for Banking Industry: A Qualitative Study of AI Applications and Challenges,” *Cybernetics and Systems*, 2022.

[71] M. Macas, C. Wu, and W. Fuertes, “A survey on deep learning for cybersecurity: Progress, challenges, and opportunities,” *Computer Networks*, vol. 212, 2022.

[72] Freepik, “Possible threats concerned with the emergence of AI,” 2020.

[73] M. Malik, M. Kumar, V. Kumar, A. K. Gautam, S. Verma, S. Kumar, and D. Goyal, “High level browser security in cloud computing services from cross site scripting attacks,” *Journal of Discrete Mathematical Sciences and Cryptography*, vol. 25, no. 4, pp. 1073–1081, 2022.

[74] P. J. Taylor, T. Dargahi, A. Dehghantanha, R. M. Parizi, and K. K. R. Choo, “A systematic literature review of blockchain cyber security,” *Digital Communications and Networks*, vol. 6, no. 2, pp. 147–156, 2020.

[75] Businesswire, “Global Artificial Intelligence-Based Cybersecurity Market 2018-2022 | Increasing Vulnerability to Cyber-Threats to Boost Growth | Technavio,” tech. rep., 2018.

[76] L. S. Nishad, R. Pandey, Akriti, S. Beniwal, J. Paliwal, and S. Kumar, “Security, privacy issues and challenges in cloud computing: A survey,” *ACM International Conference Proceeding Series*, vol. 04-05-Marc, 2016.

[77] N. K. Singh, S. K. Pandey, M. Nagalakshmi, A. A. Kumar, M. Tiwari, and S. Kumar, “Artificial Intelligence-based cloud computing for Industry 5.0,” *Proceedings - 2022 2nd International Conference on Innovative Sustainable Computational Technologies, CISCT 2022*, 2022.

[78] W. Ahmad, A. Rasool, A. R. Javed, T. Baker, and Z. Jalil, “Cyber security in IoT-based cloud computing: A comprehensive survey,” *Electronics (Switzerland)*, vol. 11, no. 1, 2022.

[79] A. Clim, “Cyber Security Beyond the Industry 4.0 Era. A Short Review on a Few Technological Promises,” *Informatica Economica*, vol. 23, no. 2/2019, pp. 34–44, 2019.

[80] Z. Zhang, H. A. Hamadi, E. Damiani, C. Y. Yeun, and F. Taher, “Explainable Artificial Intelligence Applications in Cyber Security: State-of-the-Art in Research,” *IEEE Access*, vol. 10, pp. 93104–93139, 2022.

[81] S. Kumar, B. Kumari, and A. Sharma, “A Purposed Approach from Artificial Intelligence Problems with 4 Problem Characteristics,” in *Proceedings of the 12th INDIACom*, pp. 4094–4096, 2018.

[82] S. Kumar, P. Kumar, S. Pal Singh, and A. Saxena, “A New Approach for Providing Security Mechanism in Cloud with Possible Solutions and Results,” *International Journal of Computer Applications*, vol. 67, no. 12, pp. 30–33, 2013.

[83] B. Dash, M. F. Ansari, P. Sharma, and A. Ali, “Threats and Opportunities with AI-based Cyber Security Intrusion Detection: A Review,” *International Journal of Software Engineering & Applications*, vol. 13, no. 5, pp. 13–21, 2022.

[84] A. Razzaque, “Artificial Intelligence and IT Governance: A Literature Review,” *Studies in Computational Intelligence*, vol. 974, pp. 85–97, 2021.

[85] P. Henman, “Improving public services using artificial intelligence: possibilities, pitfalls, governance,” *Asia Pacific Journal of Public Administration*, vol. 42, no. 4, pp. 209–221, 2020.

[86] P. Robles and D. J. Mallinson, “Catching up with AI: Pushing toward a cohesive governance framework,” *Politics and Policy*, 2023.

Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in
e-ISSN: 3009-075X

AN PUBLISHING

Volume 2 Issue 3

Article Number: 23068

A Mini-Review of the Environmental Footprint of Lithium-Ion Batteries for Electric Vehicles

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Abstract

The pressing requirement to combat climate change and reduce greenhouse gas emissions has catalyzed the development of sustainable mobility solutions. This review presents a detailed analysis of the environmental issues associated with traditional transportation systems, highlighting the significant role of sustainable mobility in addressing these challenges. Important strategies, including electric vehicles (EVs), mass transit, active transportation, and innovative mobility options, are examined. The review accentuates the necessity to cultivate more habitable communities, diminish emissions, enhance air quality, elevate energy efficiency, and contribute to a prosperous future through the adoption of sustainable mobility. The transition to sustainable transportation necessitates comprehensive policies, enabling regulations, and public participation. The creation and implementation of sustainable mobility strategies, the promotion of cleaner products and methods, and the fostering of collaboration across various sectors are pivotal roles for governments, legislators, and stakeholders. Additionally, public awareness campaigns and educational programs can drive behavioral changes and encourage the adoption of sustainable mobility solutions.

Keywords: Sustainability; Electric Vehicles; Emissions; Public Transit; Lithium-Ion Batteries

1 Introduction

The rise in popularity of sustainable mobility solutions can be attributed to the ongoing global climate change and an urgent need to reduce greenhouse gas emissions. Electric vehicles (EVs), powered by lithium-ion batteries, offer potential reductions in emissions and improvements in air quality. Owing to their high energy density, fast charging capabilities, and extended driving ranges, lithium-ion batteries have revolutionized the automotive industry [1, 2]. As EV sales trend upwards, the production, utilization, and disposal of lithium-ion batteries warrant closer scrutiny to ensure minimal environmental harm. A common method to evaluate the environmental impact of lithium-ion batteries is through lifecycle analysis (LCA). This approach assesses the environmental impact of a system or product across all stages of its life cycle, including raw material extraction, manufacturing, usage, and disposal. Lifecycle analysis has been applied extensively in environmental impact studies on lithium-ion batteries. For instance, Ellingsen [3] explored the environmental implications of Nordic lithium-ion batteries, highlighting the importance of the electricity generation mix, materials, and energy sources during the usage phase. Majeau-Bettez et al. [4] conducted a life cycle assessment (LCA) on lithium-ion batteries, comparing their environmental performance to that of internal combustion engines. The environmental advantages of electric vehicles are largely dependent on the lifespan of the battery and the source of electricity generation. Understanding the environmental impacts of lithium-ion batteries for electric vehicles is

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Received: 07 July 2023; **Revised:** 25 July 2023; **Accepted:** 11 August 2023; **Published:** 31 August 2023

DOI: 10.57159/gadl.jcmm.2.3.23068.

crucial for regulators, manufacturers, and consumers as it can guide the development of energy-efficient manufacturing, the integration of renewable energy, and end-of-life management.

Such understanding can help increase the viability of electric vehicles and foster the growth of the low-carbon transportation industry. This study delves into the environmental impact of lithium-ion batteries in EVs, with a focus on their production, use, and end-of-life management. The aim is to contribute valuable insights into EV sustainability and potential strategies to minimize their environmental impact. The extraction and processing of raw materials for lithium-ion batteries is the first aspect to be examined, including the environmental effects of lithium, cobalt, nickel, and graphite extraction. Knowledge of these effects can lead to the identification of environmentally friendly mining methods, policies, and technologies [5]. Next, the environmental impact of battery manufacturing is evaluated. Given that battery production necessitates energy, chemicals, and waste, suggestions for reducing energy consumption, emissions, and waste can be made to foster sustainable manufacturing. Following this, the environmental performance of lithium-ion batteries during usage is assessed, which involves evaluating indirect emissions from battery use and the power mix for EV charging. A comparison of lithium-ion batteries with internal combustion engine vehicles provides an opportunity to gauge their environmental benefits. Lastly, the administration of lithium-ion batteries at the end of their life cycle is investigated, focusing on battery recycling and resource recovery. Promoting efficient recycling and the circular economy can help reduce waste, conserve valuable resources, and mitigate environmental risks.

2 Life Cycle Assessment (LCA) for Lithium-Ion Batteries

Life Cycle Assessment (LCA) is a process that quantifies the environmental impact of a product or system throughout its entire life cycle, from raw material extraction to end-of-life management. It's an indispensable tool for gauging the environmental impacts and enhancing the sustainability of lithium-ion batteries used in Electric Vehicles (EVs) [6]. The LCA process begins with the goal and scope definition, determining the purpose, parameters, and objectives of the study. For a lithium-ion battery, its energy capacity serves as the functional unit, and the scope includes all processes from raw material extraction to end-of-life management. Following this, the inventory analysis phase collects and quantifies energy flows, inputs, and outputs from each life cycle stage to form a Life Cycle Inventory (LCI) [7]. The LCI data are then categorized by impact category (ecotoxicity, resource depletion, human toxicity, and climate change) in the impact assessment phase. The data are then transformed into environmental impact indicators, such as carbon footprints, water footprints, and eco-indicators [8]. Finally, the interpretation step involves analyzing the LCA results to identify environmental hotspots, assess the sensitivity of the results to different parameters and assumptions, and consider impact category trade-offs [9]. The benefits of using LCA for assessing the environmental impacts of lithium-ion batteries are manifold. LCA helps in identifying environmental hotspots and suggesting ways to minimize energy consumption, emissions, or the use of hazardous materials [10]. It assists decision-makers by offering data-driven insights that can guide environmentally friendly decisions and inform policy, business standards, and eco-labeling [11]. Moreover, LCA provides a platform for comparing different battery technologies or management methods. It evaluates trade-offs among environmental impact categories and promotes eco-design and innovation in battery technology. It also addresses stakeholder concerns about the environmental impact of lithium-ion batteries [12, 13]. Taking a lifespan perspective in LCA studies allows for a more holistic assessment of lithium-ion batteries. This approach helps to avoid environmental burden shifting and provides insight into long-term consequences [12]. For instance, LCA studies that consider the entire lifespan of a battery can evaluate degradation, performance reduction, and the need for replacement or refurbishment. They can also assess the environmental benefits of battery reuse or second-life usage [14]. Furthermore, LCA studies can consider the environmental impact of disposal and recycling of lithium-ion batteries, guiding the reduction of environmental impact and promotion of the circular economy [15]. Incorporating the entire battery life cycle in the study can also guide the formulation of regulations and foster the creation of sustainable batteries.

3 Mining and Processing of Lithium-ion Battery Materials and its Environmental Consequences

Lithium-ion batteries, crucial for energy storage in electric vehicles and renewable energy systems, necessitate the use of various raw materials (Table 1). Understanding these requirements aids in assessing their environmental impact and ensuring a sustainable supply chain. Battery compositions vary based on chemistry, manufacturer, and application. Some chemistries require lithium iron phosphate ($LiFePO_4$), a cobalt substitute. The extraction and processing of these materials, however, can be environmentally hazardous. Addressing resource availability, extraction methods, energy consumption, water usage, and waste management is necessary for sustainable production. Efforts are underway to promote ethical sourcing, responsible mining, and reduced environmental impact. Substitute materials and chemistries are also being developed to reduce raw material consumption [16]. The extraction of lithium-ion battery raw materials like lithium, cobalt, nickel, graphite, manganese, aluminum, and copper may have negative environmental impacts. These include deforestation, habitat degradation, soil degradation, and water and air pollution. Mining and refining can emit greenhouse gases and pollute the air with dust and emissions like CO_2 and CH_4. Additionally, high-energy processes involved in extraction and fossil fuel usage for energy may result in increased carbon emissions and environmental problems. Mismanagement of mining waste can result in trash mounds and contamination, depleting land resources while polluting the soil and water [17]. Sustainable practices, such as strict environmental laws and monitoring programs, land restoration, transparency and responsible sourcing, and the promotion of recycling and the circular economy, are needed to mitigate these effects.

Table 1: Characteristics of raw materials used in lithium-ion batteries.

Raw Material	**Function**	**Extracting Methods**	**Major Producing Nations**
Lithium	Helps batteries function for a long time and has a high energy density [18]	Mining from hard rock resources and extraction from brine deposits [19]	Australia, Chile, Argentina, China
Cobalt	Increases battery's energy density and stability	Mostly produced in the Democratic Republic of the Congo (DRC)	Democratic Republic of the Congo (DRC)
Nickel	Enhances overall performance and energy density [20]	Mined and processed from sulfide and laterite ores	Russian Federation, Philippines, Indonesia
Graphite	Anode material, stores and releases lithium ions	Natural graphite: China, Brazil, India; Synthetic graphite: Primarily made in China and Japan from petroleum coke	China, Brazil, India, China, Japan
Manganese	Supports battery stability and security [21]	Mined and processed from manganese ores	South Africa, Australia, Gabon
Aluminum and Copper	Current collectors and conductive materials	Mined and refined in numerous nations across the world	All over the world

4 Responsible Mining Regulations and Case Studies

To lessen mining's environmental impact, sustainable practices and strict rules are required. Environmental Impact Assessments (EIAs) help in assessing the environmental and social impacts of mining while rehabilitating mined areas and preserving biodiversity forms part of sustainable mining. Other crucial aspects include effective water management, energy efficiency, waste management, community participation, and responsible sourcing. These practices and legal compliance help to lessen the environmental impact of lithium-ion battery raw material extraction while benefiting regional populations and ecosystems [22–25]. Several initiatives and certification programs, like the Initiative for Responsible Mining Assurance (IRMA) and the Responsible Minerals Initiative (RMI), encourage ethical sourcing of raw materials. These initiatives support human rights, fair labor practices, and discourage illegal mining [26]. Case studies on raw material extraction further highlight extraction challenges and opportunities, which can be summarized as follows:

- Cobalt Mining in the Democratic Republic of the Congo (DRC): Issues of deforestation, water pollution, and child labor have been associated with cobalt mining, emphasizing the need for responsible sourcing, transparent supply chains, and environmentally friendly mining [27].
- Nickel mining in New Caledonia: Mining has resulted in habitat loss, soil erosion, and water contamination. Sustainable mining practices and communication with local communities can mitigate these effects.
- Lithium extraction in Bolivia, Chile, and Argentina: The studies have emphasized the need for effective water management systems due to the impact on fragile ecosystems and water resources.
- Graphite mining in China: The industry faces challenges related to air pollution, worker health, and waste management. Improving safety and environmental standards in graphite mining is necessary to protect human health and the environment [28].

In conclusion, these case studies and research findings demonstrate the challenges of extracting lithium-ion battery materials and the need for all stakeholders to work together in promoting sustainable mining. By employing responsible raw material extraction methods, the lithium-ion battery industry can reduce environmental impacts while improving social outcomes [29, 30].

5 Sustainable Battery Production

The battery industry, pivotal in producing lithium-ion batteries for electric vehicles (EVs) and other applications, requires substantial energy and resources. Particularly, the production of cathodes and anodes for batteries necessitates laborious and energy-intensive processes. Techniques such as heat sealing or ultrasonic welding for encapsulating battery cells are also energy-demanding, necessitating a focus on energy efficiency [31, 32]. Manufacturing lithium-ion batteries also involves the use of various chemicals and materials, key to the operation, safety, and performance of the battery. These include lithium salts, organic solvents, cathode materials, anodes, separators, binders, conductive additives, and current collectors [14, 33–35].

The choice of these chemicals and materials significantly influences the performance, safety, and environmental sustainability of batteries. Significant environmental issues can arise from the manufacturing of lithium-ion batteries. These primarily stem from greenhouse gas emissions from energy generation, raw material extraction and processing, electrode manufacturing, cell assembly, and other industrial processes [5, 36, 37]. To meet rising demand while minimizing environmental harm, it is essential to adopt several sustainable practices. These practices include enhancing energy efficiency, incorporating renewable energy, promoting recycling and waste reduction, implementing sustainable material sourcing, optimizing water and chemical management, and taking into account lifecycle impacts [38–41]. Efforts to enhance energy efficiency in battery production can include advanced manufacturing technologies, process optimization, use of renewable energy sources, and adopting a lifecycle approach [42, 43]. To reduce the environmental impact of battery production, measures such as energy efficiency, use of renewable energy, responsible material sourcing, chemical management, and recycling and circular economy can be implemented. Effective recycling technologies can recover valuable materials from used batteries, reducing waste and the need for new raw material mining [44]. Furthermore, collaboration among manufacturers, industry groups, policymakers, and research organizations is crucial for developing sustainable practices and industry standards. This can help reduce energy consumption, carbon emissions, and improve the overall sustainability of battery manufacturing.

6 Vehicle Operation, Charging, and Comparison

Electric vehicles (EVs) primarily employ lithium-ion batteries as their energy storage technology, which significantly influences their performance, driving comfort, and range [45]. The battery power, which enables rapid acceleration, and the use of regenerative braking, underline the efficiency of the electric propulsion system. EVs also use advanced Battery Management Systems (BMS) to monitor temperature, voltage, and state of charge, thus ensuring battery performance, security, and longevity [46]. Charging EVs is facilitated by charging stations, which can range from home units to public fast-charging stations. The energy generation mix employed to charge EV batteries impacts the indirect emissions of EV operation. The mix can consist of nuclear, renewable, and fossil fuels (coal, natural gas, and oil), with the type of energy sources used greatly affecting the carbon dioxide and overall environmental impact of EV operation [47]. The transition to renewable energy in power generation is crucial for reducing indirect emissions from EV operation. Moreover, the use of smart charging and grid flexibility can optimize the use of renewable energy and reduce indirect emissions. Vehicle-to-grid (V2G) technology can further enhance renewable energy integration and grid stability [48]. Effective charging infrastructure, including considerations of efficiency, accessibility, grid integration, and renewable energy usage, can improve EV convenience and reduce environmental impact. A comprehensive life cycle assessment (LCA) should consider both direct and indirect emissions to accurately evaluate the environmental impact of EVs and the charging infrastructure [49, 50]. When comparing internal combustion engines (ICEs) with EVs, aspects such as performance, efficiency, and environmental impact come into play. EVs have numerous advantages over ICEs, including reduced energy consumption, decreased pollution, lower operating and maintenance costs, and noise reduction [51]. However, challenges, including a shorter range and slower refueling, persist. Nevertheless, improvements in technology and charging infrastructure are mitigating these issues, positioning EVs as a promising alternative to ICEs for a sustainable future [52].

7 End-of-Life Management of EV Lithium-Ion Batteries

The longevity of lithium-ion batteries is crucial to electric vehicle (EV) battery end-of-life management. An EV's lithium-ion battery lifespan is determined by factors like battery chemistry, usage, operational conditions, and management. Typically, these batteries can last 8–15 years or longer, with degradation gradually reducing capacity and performance [53]. After their usage in EVs, lithium-ion batteries often retain a significant amount of capacity, making them suitable for other applications like grid stabilization, backup power, and renewable energy integration. Furthermore, recycling these batteries allows the recovery of valuable materials like lithium, cobalt, nickel, and manganese, thus reducing the need for extracting fresh raw materials [54]. Proper battery disposal is crucial to reducing the environmental impact of these batteries. When improperly disposed of, batteries can release harmful elements into the environment. To mitigate this, battery recycling helps conserve precious resources and promotes resource sustainability [55]. Effective battery recycling requires efficient collection, separation, safe transportation, and handling. Different battery chemistries require different recycling methods, making the sorting process crucial for material recovery. Recycling facilities need to follow set standards for battery handling, transportation, and recycling, to avoid environmental damage and legal issues [56, 57]. Battery recycling faces several challenges including complex battery chemistries, increased volume of used batteries, safety concerns, insufficient infrastructure, environmental implications, and achieving high material recovery rates [54, 58]. Overcoming these challenges requires collaborative efforts from researchers, industries, and governments. In summary, effective end-of-life management of EV lithium-ion batteries involves maximizing their lifespan, exploring second-life uses, and ensuring efficient recycling. These practices can lead to a more circular economy for EV batteries, optimizing value, reducing waste, and improving electric mobility.

8 Life Cycle Assessment Studies on Lithium-Ion Batteries for EVs

8.1 Selected LCA Studies and Comparative Analysis

Numerous Life Cycle Assessment (LCA) studies have evaluated the environmental footprint of lithium-ion batteries for Electric Vehicles (EVs), providing valuable sustainability insights. This section scrutinizes notable LCA studies on lithium-ion batteries for EVs, focusing on methodologies, assumptions, critical findings, and comparative analyses. LCA studies follow principles outlined in ISO 14040:2006 [59], providing a comprehensive life cycle evaluations framework. They consider facets of the battery life cycle, including raw material extraction, battery manufacturing, vehicle operation, and end-of-life management. Identifying system boundaries is crucial, including the functional unit to express the functional performance of the battery, such as energy capacity or lifespan mileage. LCA results are often compared to offer valuable insights into EVs' environmental sustainability by comparing life cycle effects of various battery technologies and manufacturing processes. For instance, according to numerous LCA studies, lithium-ion battery-powered EVs emit fewer greenhouse gases than conventional internal combustion engine (ICE) vehicles [60, 61]. Most pollutants stem from the battery's manufacturing process, and the mix of power generation utilized during the operational phase significantly influences the potential overall reduction in emissions. Comparative LCA studies serve as valuable resources for stakeholders in the EV and battery industries, as well as policymakers. Research findings can be leveraged to craft regulations, standards, and incentives that promote the adoption of EVs and environmentally friendly battery production.

8.2 Identification of Data Gaps and Uncertainties

Reliable data is critical for accurately assessing the environmental impact of lithium-ion batteries for EVs. Although LCA studies offer valuable information about the viability of battery technologies, it is crucial to recognize and address data gaps and uncertainties. Obtaining accurate data on the extraction and processing of raw materials used in lithium-ion batteries is a major challenge in LCA studies. Data gaps on the environmental impacts of mining operations, especially in countries with less transparent reporting systems, are prevalent. Accurate impact assessment is further complicated by scarce data on energy use and emissions associated with raw material extraction. LCA studies on lithium-ion batteries for EVs can yield a range of outcomes using various impact assessment methods. Selection of impact categories, characterization criteria, and weighting factors can influence results. Maintaining consistency and comparability across studies can be challenging, especially when different LCA databases and tools are used. Researchers, industry stakeholders, and policymakers need to work collectively to address data gaps and uncertainties in LCA studies on lithium-ion batteries for EVs. By acknowledging and addressing these data gaps and uncertainties, LCA studies can provide more comprehensive and insightful assessments of the environmental impacts of lithium-ion batteries for EVs.

9 Policy Implications, Future Directions, and Innovations in Battery Technology

Life cycle assessment (LCA) studies highlight the environmental implications of lithium-ion batteries used in electric vehicles (EVs). Their findings can guide policy decisions and steer research towards sustainable transportation practices. This comprehensive overview brings together the primary areas for policy consideration, strategies for promoting sustainable battery production and recycling, research and development priorities, and potential future innovations in EV battery technology.

9.1 Policy and R&D Considerations for Sustainable Battery Practices

LCA studies unveil the environmental hotspots and impacts associated with battery production, emphasizing the necessity for adequate recycling and end-of-life management. Therefore, policies should prioritize sustainable battery manufacturing practices, such as using cleaner energy sources, improving process efficiency, and incorporating less hazardous materials [62, 63]. The establishment of comprehensive recycling infrastructure and collection systems can optimize resource recovery and minimize environmental pollution. Encouraging collaboration among academia, industry, and government can spur innovation in battery chemistry, manufacturing methodologies, and recycling technologies. This involves funding research initiatives that focus on energy-efficient manufacturing processes, sustainable battery materials, and advanced recycling procedures. These actions can expedite the progression of greener battery technology and a more sustainable transportation industry [1, 63–65]. Policy interventions must establish environmental standards and rules for battery production, focusing on minimizing the environmental impacts associated with raw material extraction, production procedures, and waste management. Regulations limiting resource use, pollution, and the use of hazardous materials can motivate companies to adopt more eco-friendly production methods. Moreover, robust certification programs that assess batteries' environmental performance can guide consumers towards greener products.

9.2 Future Improvements and Innovations in EV Battery Technology

Future prospects for EV battery technologies are promising, with an array of potential enhancements on the horizon. These include enhancing energy density to facilitate extended driving ranges, advancements in charging infrastructure to reduce charging times, increasing battery lifespan and endurance to minimize environmental impact, and cost reduction to make EVs more affordable and competitive [66]. Furthermore, enhancements in environmental sustainability throughout a battery's lifetime are essential. This involves mitigating environmental impacts of raw material extraction, refining production processes to minimize energy use and waste, and developing efficient recycling and resource recovery methods. Exploration of sustainable and alternative materials like lithium from geothermal brines and cobalt-free cathode chemistries can alleviate environmental concerns associated with battery production [67, 68]. Finally, future EV battery technology can aid in integrating renewable energy sources. Enhancements in energy storage technology can accelerate broad adoption of renewable energy systems by enabling efficient energy storage and grid integration. Through implementing these strategies, policies, and research priorities, it is possible to foster an environment conducive to the sustainable development and deployment of lithium-ion batteries for EVs. Collaboration, innovation, and informed decision-making are paramount to establishing a more environmentally friendly and sustainable transportation industry.

10 Conclusion

This paper offers an extensive study on the environmental impacts of lithium-ion batteries in electric vehicles (EVs), examining each phase of their lifecycle: extraction of raw materials, battery manufacturing, vehicle operation, and end-of-life management. The research highlights the importance of Life Cycle Assessment (LCA) for evaluating the environmental influence of lithium-ion batteries. It provides a comprehensive understanding from the stage of raw material extraction to the end-of-life management. Further, this study deliberates on the environmental effects of lithium-ion battery extraction and manufacturing, emphasizing the critical need for sustainable practices and legislative measures for impact mitigation. It underlines the necessity for a transition to renewable energy sources to reduce indirect emissions resulting from EV charging, brought to focus through an examination of the role of lithium-ion batteries in EV operation. This paper also sheds light on the significance of efficient end-of-life management for EV batteries, spotlighting potential recycling methods and strategies for resource recovery to alleviate environmental concerns and increase resource efficiency. It also provides a wide-ranging literature review on the environmental impact of lithium-ion batteries for EVs through a review of numerous LCA studies, thereby aiding comprehension and informed decision-making. Finally, the study accentuates the need for fostering environmentally friendly battery manufacturing and recycling practices through supportive regulations and incentives. With these findings, several key recommendations are proposed for future research and practice in the realm of lithium-ion batteries for EVs. These include conducting long-term environmental impact assessments, encouraging technological advancements, adopting a circular economy approach, assessing policy effectiveness, enhancing stakeholder engagement, creating standardized reporting frameworks, and exploring effective public outreach strategies and educational initiatives. This study enhances the understanding of the environmental impact of lithium-ion batteries for EVs, supporting the ongoing efforts to create a more sustainable transportation sector. Emphasizing the importance of a life cycle view when assessing the environmental impact of lithium-ion batteries for EVs, it underscores the need for sustainable practices across all stages - from ethical raw material extraction and efficient manufacturing to effective end-of-life planning. The insights presented herein can guide policymakers, industry stakeholders, and researchers in the transition toward a greener and sustainable transportation system.

Declaration of Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Declaration

This research did not receive any grants from governmental, private, or nonprofit funding bodies.

Author Contribution

Sarvesh Kumar: Conceptualization, Methodology, Supervision, Writing - review and editing. **Upasana Gupta**: Investigation, Visualization, Writing - original draft. **Arvind Kumar Singh**: Investigation, Visualization, Writing - original draft. **Avadh Kishore Singh**: Resources, Investigation, Visualization, Writing - original draft.

References

[1] R. Nealer and T. Hendrickson, "Review of recent lifecycle assessments of energy and greenhouse gas emissions for electric vehicles," *Current Sustainable/Renewable Energy Reports*, vol. 2, pp. 66–73, 2015.

[2] Z. Zhou, Y. Lai, Q. Peng, and J. Li, "Comparative life cycle assessment of merging recycling methods for spent lithium ion batteries," *Energies*, vol. 14, no. 19, p. 6263, 2021.

[3] S. Illikainen, "Environmental impacts of lithium-ion batteries," B.S. thesis, S. Illikainen, 2022.

[4] G. Majeau-Bettez, T. R. Hawkins, and A. H. Strømman, "Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles," *Environmental science & technology*, vol. 45, no. 10, pp. 4548–4554, 2011.

[5] I. Rey, C. Vallejo, G. Santiago, M. Iturrondobeitia, and E. Lizundia, "Environmental impacts of graphite recycling from spent lithium-ion batteries based on life cycle assessment," *ACS Sustainable Chemistry & Engineering*, vol. 9, no. 43, pp. 14488–14501, 2021.

[6] D. A. Notter, M. Gauch, R. Widmer, P. Wager, A. Stamp, R. Zah, and H.-J. Althaus, "Contribution of li-ion batteries to the environmental impact of electric vehicles," 2010.

[7] J. F. Peters, M. Baumann, B. Zimmermann, J. Braun, and M. Weil, "The environmental impact of li-ion batteries and the role of key parameters–a review," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 491–506, 2017.

[8] Y. Gong, Y. Yu, K. Huang, J. Hu, and C. Li, "Evaluation of lithium-ion batteries through the simultaneous consideration of environmental, economic and electrochemical performance indicators," *Journal of Cleaner Production*, vol. 170, pp. 915–923, 2018.

[9] A. Ramos, C. Afonso Teixeira, and A. Rouboa, "Environmental analysis of waste-to-energy—a portuguese case study," *Energies*, vol. 11, no. 3, p. 548, 2018.

[10] L. M. I Canals, G. Burnip, and S. Cowell, "Evaluation of the environmental impacts of apple production using life cycle assessment (lca): case study in new zealand," *Agriculture, Ecosystems & Environment*, vol. 114, no. 2-4, pp. 226–238, 2006.

[11] M. D. Chatzisideris, N. Espinosa, A. Laurent, and F. C. Krebs, *Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies*, vol. 156. Elsevier, 2016.

[12] X. Domènech, J. A. Ayllón, J. Peral, and J. Rieradevall, "How green is a chemical reaction? application of lca to green chemistry," *Environmental science & technology*, vol. 36, no. 24, pp. 5517–5520, 2002.

[13] C. De Camillis, M. Brandão, A. Zamagni, and D. Pennington, "Sustainability assessment of future-oriented scenarios: a review of data modelling approaches in life cycle assessment," *Towards Recommendations for Policy Making and Business Strategies*, pp. 1–90, 2013.

[14] M. Zackrisson, K. Fransson, J. Hildenbrand, G. Lampic, and C. O'Dwyer, "Life cycle assessment of lithium-air battery cells," *Journal of Cleaner Production*, vol. 135, pp. 299–311, 2016.

[15] J. Diekmann, C. Hanisch, L. Froböse, G. Schälicke, T. Loellhoeffel, A.-S. Fölster, and A. Kwade, "Ecological recycling of lithium-ion batteries from electric vehicles with focus on mechanical processes," *Journal of the Electrochemical Society*, vol. 164, no. 1, p. A6184, 2016.

[16] G. Shrestha, P. D. Stahl, and L. Ingram, "Influence of reclamation management practices on soil bulk density and infiltration rates on surface coal mine lands in wyoming," in *National Meeting of the American Society of Mining and Reclamation*, pp. 1042–1056, ASMR Lexington, KY, 2005.

[17] M. R. Sabour, E. Alam, and A. M. Hatami, "Global trends and status in landfilling research: a systematic analysis," *Journal of Material Cycles and Waste Management*, vol. 22, pp. 711–723, 2020.

[18] W. Qiu, Q. Hao, S. H. K. Annamareddy, B. Xu, Z. Guo, and Q. Jiang, "Electric vehicle revolution and implications: ion battery and energy," *Engineered Science*, vol. 20, pp. 100–109, 2022.

[19] B. Lu, J. Liu, and J. Yang, "Substance flow analysis of lithium for sustainable management in mainland china: 2007–2014," *Resources, Conservation and Recycling*, vol. 119, pp. 109–116, 2017.

[20] S. Kalluri, H. Cha, J. Kim, H. Lee, H. Jang, and J. Cho, "Building high-rate nickel-rich cathodes by self-organization of structurally stable macrovoid," *Advanced Science*, vol. 7, no. 7, p. 1902844, 2020.

[21] L. Simonelli, A. Sorrentino, C. Marini, N. Ramanan, D. Heinis, W. Olszewski, A. Mullaliu, A. Birrozzi, N. Laszczynski, M. Giorgetti, *et al.*, "Role of manganese in lithium-and manganese-rich layered oxides cathodes," *The Journal of Physical Chemistry Letters*, vol. 10, no. 12, pp. 3359–3368, 2019.

[22] B. Yilmaz and N. B. Harmancioglu, “An indicator based assessment for water resources management in gediz river basin, turkey,” *Water Resources Management*, vol. 24, pp. 4359–4379, 2010.

[23] Y. Yang, P. D. Erskine, S. Zhang, Y. Wang, Z. Bian, and S. Lei, “Effects of underground mining on vegetation and environmental patterns in a semi-arid watershed with implications for resilience management,” *Environmental Earth Sciences*, vol. 77, pp. 1–12, 2018.

[24] P. Le Billon and S. Spiegel, “Cleaning mineral supply chains? political economies of exploitation and hidden costs of technical fixes,” *Review of International Political Economy*, vol. 29, no. 3, pp. 768–791, 2022.

[25] J. A. Aznar-Sánchez, J. J. García-Gómez, J. F. Velasco-Muñoz, and A. Carretero-Gómez, “Mining waste and its sustainable management: advances in worldwide research,” *Minerals*, vol. 8, no. 7, p. 284, 2018.

[26] C. Di Noi and A. Ciroth, “Environmental and social pressures in mining. results from a sustainability hotspots screening,” *Resources*, vol. 7, no. 4, p. 80, 2018.

[27] J. A. Diemel and D. J. Hilhorst, “Unintended consequences or ambivalent policy objectives? conflict minerals and mining reform in the democratic republic of congo,” *Development Policy Review*, vol. 37, no. 4, pp. 453–469, 2019.

[28] C. Ma, Y. Zhao, J. Li, Y. Song, J. Shi, Q. Guo, and L. Liu, “Synthesis and electrochemical properties of artificial graphite as an anode for high-performance lithium-ion batteries,” *Carbon*, vol. 64, pp. 553–556, 2013.

[29] P. Liu, L. Xiao, Y. Chen, Y. Tang, J. Wu, and H. Chen, “Recovering valuable metals from linixcoymn1-x-yo2 cathode materials of spent lithium ion batteries via a combination of reduction roasting and stepwise leaching,” 2019.

[30] J. Lin, L. Li, E. Fan, C. Liu, X. Zhang, H. Cao, Z. Sun, and R. Chen, “Conversion mechanisms of selective extraction of lithium from spent lithium-ion batteries by sulfation roasting,” *ACS applied materials & interfaces*, vol. 12, no. 16, pp. 18482–18489, 2020.

[31] M. Kespe, S. Cernak, M. Gleiß, S. Hammerich, and H. Nirschl, “Three-dimensional simulation of transport processes within blended electrodes on the particle scale,” *International Journal of Energy Research*, vol. 43, no. 13, pp. 6762–6778, 2019.

[32] L. Wang, X. Cao, L. Xu, J. Chen, and J. Zheng, “Transformed akhtenskite mno2 from mn3o4 as cathode for a rechargeable aqueous zinc ion battery,” *ACS Sustainable Chemistry & Engineering*, vol. 6, no. 12, pp. 16055–16063, 2018.

[33] P. Isken, M. Winter, S. Passerini, and A. Lex-Balducci, “Methacrylate based gel polymer electrolyte for lithium-ion batteries,” *Journal of power sources*, vol. 225, pp. 157–162, 2013.

[34] G. Liu, H. Zheng, A. Simens, A. Minor, X. Song, and V. Battaglia, “Optimization of acetylene black conductive additive and pvdf composition for high-power rechargeable lithium-ion cells,” *Journal of The Electrochemical Society*, vol. 154, no. 12, p. A1129, 2007.

[35] Y. Wen, L. Shao, P. Zhao, B. Wang, G. Cao, and Y. Yang, “Carbon coated stainless steel mesh as a low-cost and corrosion-resistant current collector for aqueous rechargeable batteries,” *Journal of Materials Chemistry A*, vol. 5, no. 30, pp. 15752–15758, 2017.

[36] C. Yang, J. Zhang, Q. Jing, Y. Liu, Y. Chen, and C. Wang, “Recovery and regeneration of lifepo4 from spent lithium-ion batteries via a novel pretreatment process,” *International Journal of Minerals, Metallurgy and Materials*, vol. 28, pp. 1478–1487, 2021.

[37] J. Cheng, Y. Zhang, T. Wang, H. Xu, P. Norris, and W.-P. Pan, “Emission of volatile organic compounds (vocs) during coal combustion at different heating rates,” *Fuel*, vol. 225, pp. 554–562, 2018.

[38] M. Weeber, J. Wanner, P. Schlegel, K. P. Birke, and A. Sauer, “Methodology for the simulation based energy efficiency assessment of battery cell manufacturing systems,” *Procedia Manufacturing*, vol. 43, pp. 32–39, 2020.

[39] L. Gaines, J. Sullivan, A. Burnham, and I. Belharouak, “Life-cycle analysis of production and recycling of lithium ion batteries,” *Transportation research record*, vol. 2252, no. 1, pp. 57–65, 2011.

[40] T. Li and M. Dong, “Online control for energy storage management with renewable energy integration,” in *2013 IEEE International Conference on Acoustics, Speech and Signal Processing*, pp. 5248–5252, IEEE, 2013.

[41] Y. Poussade, F. Vince, and C. Robillot, “Energy consumption and greenhouse gases emissions from the use of alternative water sources in south east queensland,” *Water Science and Technology: Water Supply*, vol. 11, no. 3, pp. 281–287, 2011.

[42] C. S. Cheng, W. R. Liu, and F. M. Wang, “A novel ionic host solid electrolyte interface formation on reduced graphene oxide of lithium ion battery,” *Electrochimica Acta*, vol. 106, pp. 425–431, 2013.

[43] M. A. Rajaeifar, M. Raugei, B. Steubing, A. Hartwell, P. A. Anderson, and O. Heidrich, "Life cycle assessment of lithium-ion battery recycling using pyrometallurgical technologies," *Journal of Industrial Ecology*, vol. 25, no. 6, pp. 1560–1571, 2021.

[44] S. Van Ewijk, J. A. Stegemann, and P. Ekins, "Global life cycle paper flows, recycling metrics, and material efficiency," *Journal of Industrial Ecology*, vol. 22, no. 4, pp. 686–693, 2018.

[45] Y. Li, J. Song, and J. Yang, "A review on structure model and energy system design of lithium-ion battery in renewable energy vehicle," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 627–633, 2014.

[46] C.-H. Lee and C.-H. Wu, "A novel big data modeling method for improving driving range estimation of evs," *IEEE Access*, vol. 3, pp. 1980–1993, 2015.

[47] M. Noussan, R. Roberto, and B. Nastasi, "Performance indicators of electricity generation at country level—the case of italy," *Energies*, vol. 11, no. 3, p. 650, 2018.

[48] Q. Kong, M. Fowler, E. Entchev, H. Ribberink, and R. McCallum, "The role of charging infrastructure in electric vehicle implementation within smart grids," *Energies*, vol. 11, no. 12, p. 3362, 2018.

[49] P. Kumar and S. Chakrabarty, "Total cost of ownership analysis of the impact of vehicle usage on the economic viability of electric vehicles in india," *Transportation Research Record*, vol. 2674, no. 11, pp. 563–572, 2020.

[50] K. Uddin, T. Jackson, W. D. Widanage, G. Chouchelamane, P. A. Jennings, and J. Marco, "On the possibility of extending the lifetime of lithium-ion batteries through optimal v2g facilitated by an integrated vehicle and smart-grid system," *Energy*, vol. 133, pp. 710–722, 2017.

[51] N. C. Onat, M. Kucukvar, and O. Tatari, "Conventional, hybrid, plug-in hybrid or electric vehicles? state-based comparative carbon and energy footprint analysis in the united states," *Applied Energy*, vol. 150, pp. 36–49, 2015.

[52] E. Bulut and M. C. Kisacikoglu, "Mitigating range anxiety via vehicle-to-vehicle social charging system," in *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, pp. 1–5, IEEE, 2017.

[53] Z. Tian, L. Tu, C. Tian, Y. Wang, and F. Zhang, "Understanding battery degradation phenomenon in real-life electric vehicle use based on big data," in *2017 3rd International Conference on Big Data Computing and Communications (BIGCOM)*, pp. 334–339, IEEE, 2017.

[54] F. Wang, T. Zhang, Y. He, Y. Zhao, S. Wang, G. Zhang, Y. Zhang, and Y. Feng, "Recovery of valuable materials from spent lithium-ion batteries by mechanical separation and thermal treatment," *Journal of cleaner production*, vol. 185, pp. 646–652, 2018.

[55] Y. Yu, B. Chen, K. Huang, X. Wang, and D. Wang, "Environmental impact assessment and end-of-life treatment policy analysis for li-ion batteries and ni-mh batteries," *International journal of environmental research and public health*, vol. 11, no. 3, pp. 3185–3198, 2014.

[56] S.-S. Lin and K.-H. Chiu, "An evaluation of recycling schemes for waste dry batteries–a simulation approach," *Journal of Cleaner Production*, vol. 93, pp. 330–338, 2015.

[57] M. P. Krekeler, H. A. Barrett, R. Davis, C. Burnette, T. Doran, A. Ferraro, and A. Meyer, "An investigation of mass and brand diversity in a spent battery recycling collection with an emphasis on spent alkaline batteries: Implications for waste management and future policy concerns," *Journal of Power Sources*, vol. 203, pp. 222–226, 2012.

[58] E. Gratz, Q. Sa, D. Apelian, and Y. Wang, "A closed loop process for recycling spent lithium ion batteries," *Journal of Power Sources*, vol. 262, pp. 255–262, 2014.

[59] *Environmental management: life cycle assessment; Principles and Framework*. ISO, 2006.

[60] R. Tolomeo, G. De Feo, R. Adami, and L. Sesti Osséo, "Application of life cycle assessment to lithium ion batteries in the automotive sector," *Sustainability*, vol. 12, no. 11, p. 4628, 2020.

[61] M. P. Mahmud, N. Huda, S. H. Farjana, and C. Lang, "Comparative life cycle environmental impact analysis of lithium-ion (liio) and nickel-metal hydride (nimh) batteries," *Batteries*, vol. 5, no. 1, p. 22, 2019.

[62] L. Unterreiner, V. Jülch, and S. Reith, "Recycling of battery technologies–ecological impact analysis using life cycle assessment (lca)," *Energy Procedia*, vol. 99, pp. 229–234, 2016.

[63] Q. Wang, W. Liu, X. Yuan, H. Tang, Y. Tang, M. Wang, J. Zuo, Z. Song, and J. Sun, "Environmental impact analysis and process optimization of batteries based on life cycle assessment," *Journal of cleaner production*, vol. 174, pp. 1262–1273, 2018.

[64] R. Faria, P. Marques, P. Moura, F. Freire, J. Delgado, and A. T. De Almeida, "Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 271–287, 2013.

[65] Y. Gupt and S. Sahay, “Review of extended producer responsibility: A case study approach,” *Waste Management & Research*, vol. 33, no. 7, pp. 595–611, 2015.

[66] L. Rubino, C. Capasso, and O. Veneri, “Review on plug-in electric vehicle charging architectures integrated with distributed energy sources for sustainable mobility,” *Applied Energy*, vol. 207, pp. 438–464, 2017.

[67] H. Ambrose, D. Gershenson, A. Gershenson, and D. Kammen, “Driving rural energy access: a second-life application for electric-vehicle batteries,” *Environmental Research Letters*, vol. 9, no. 9, p. 094004, 2014.

[68] J. F. Peters, M. Baumann, and M. Weil, “The importance of recyclability for the environmental performance of battery systems,” in *Cascade Use in Technologies 2018: Internationale Konferenz zur Kaskadennutzung und Kreislaufwirtschaft–Oldenburg 2018*, pp. 104–110, Springer Berlin Heidelberg, 2019.